Journal of Earth Science, *Vol. 29*, *No. 2*, *p. 307–325*, *April 2018* *ISSN 1674-487X*
Printed in China
https://doi.org/10.1007/s12583-017-0904-8

Multi-Stage Basin Development and Hydrocarbon Accumulations: A Review of the Sichuan Basin at Eastern Margin of the Tibetan Plateau

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ABSTRACT: Sichuan Basin is one of the uppermost petroliferous basins in China. It experienced three evolutionary phases which were marine carbonate platform (Ediacaran to Late Triassic), Indosinian-Yanshanian orogeny foreland basin (Late Triassic to Late Cretaceous) and uplift and tectonic modification (Late Cretaceous to Quaternary). The present-day tectonics of the Sichuan Basin and its periphery are characterized by three basic elements which are topography, basement type and surface structure, and two settings (plate margin and interior). Therefore, be subdivided into five units which have different structure and tectonic history. The basin contains five different sets of source rocks with thickness up to 2 500 m. These source rocks were well preserved due to the presence of Middel–Lower Triassic evaporites (>~200 m) and thick terrestrial sediments filling in the Indosinian-Yanshanian foreland basin (>3 000 m). The uplift and erosion since Late Cretaceous has significant influence on cross-strata migration and accumulation of oil and gas. The multi-phase evolution of the basin and its superimposed tectonic elements, good petroleum geologic conditions and diverse petroleum systems reveal its bright exploration prospects.

KEY WORDS: multi-stage basin, hydrocarbon accumulation, Sichuan Basin, eastern margin of the Tibetan Plateau.

0 INTRODUCTION

The Sichuan Basin is one of the largest petroliferous sedimentary basins in China. As early as ~1100 CE ago, people has used bamboo casing and piping to drilled brine/natural gas near Zigong in the southern Sichuan Basin (Zhong and Huang, 1997). The first significant Triassic gas pools were discovered in Shiyougou and Shengdengshan structures in the 1930's with a series of oil/gas discoveries later on (Fig. 1), e.g., Well Long-10 in 1957, Well Nv-2 in 1958 and Well Wei-117 in 1964, Well Chuan-104 in 1984, etc. (Ma et al., 2010; Liu et al., 2008a; Zhang and Zhang, 2002; Xu and Shen, 1996; Korsch et al., 1991). Recent major discoveries include Puguang Gasfield in 2003 in the eastern Sichuan (Liu et al., 2017; Zou et al., 2014; Ma et al., 2007), Guang'an Gasfield in 2006 in the center of the basin (Chen et al., 2007), and the Anyue Gasfield also in the central Sichuan Basin in 2013, the latter representing the biggest gasfield at present in China (Zou et al., 2014). The total proven in-place gas volume found in the Sichuan Basin is 2.6×10^{12} m^3. Thus, it is timely to review the geological features of the Sichuan Basin and its hydrocarbon accumulations, to better understand petroleum and gas systems in the basin. This review of geological basin is based on analyses of oil/gas accumulations in exploratory wells and decades of field studies in the Sichuan Basin. It may provide better understanding of the geology and hydrocarbon occurrences in other tectonically complex basins.

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Manuscript received July 22, 2016.
Manuscript accepted August 1, 2016.

1 TECTONIC SETTING

Sichuan Basin locates in the western margin of the South China Block that is comprised by the Yangtze Platform in the northwest and the Cathaysian Block in the southeast (Fig. 1). To the north, it is separated from the North China Block by the Late Paleozoic to Middle Mesozoic Qinling Orogen (Dong et al., 2011), and to the west from the Mesozoic–Cenozoic Eastern Tibetan Plateau by the Longmen-Daliang thrust fold belt (Liu et al., 2012; Robert et al., 2010). The Qinling Orogen experienced a protracted tectonic history, and is considered to have undergone a two-phase collision along Shangdan and Mianlüe suture zones in the Middle Paleozoic and Mid-to-Late Triassic periods, respectively. In particular, the later diachronous collision of the North and South China blocks along the Mianlüe suture zone had exerted a profound impact on the evolution of the Sichuan Basin (Liu S G et al., 2005), even the whole Yangtze Platform.

Furthermore, there are two tectonic phases that in general

Liu, S. G., Deng, B., Jansa, L., et al., 2018. Multi-Stage Basin Development and Hydrocarbon Accumulations: A Review of the Sichuan Basin at Eastern Margin of the Tibetan Plateau. *Journal of Earth Science*, 29(2): 307–325. https://doi.org/10.1007/s12583-017-0904-8. http://en.earth-science.net

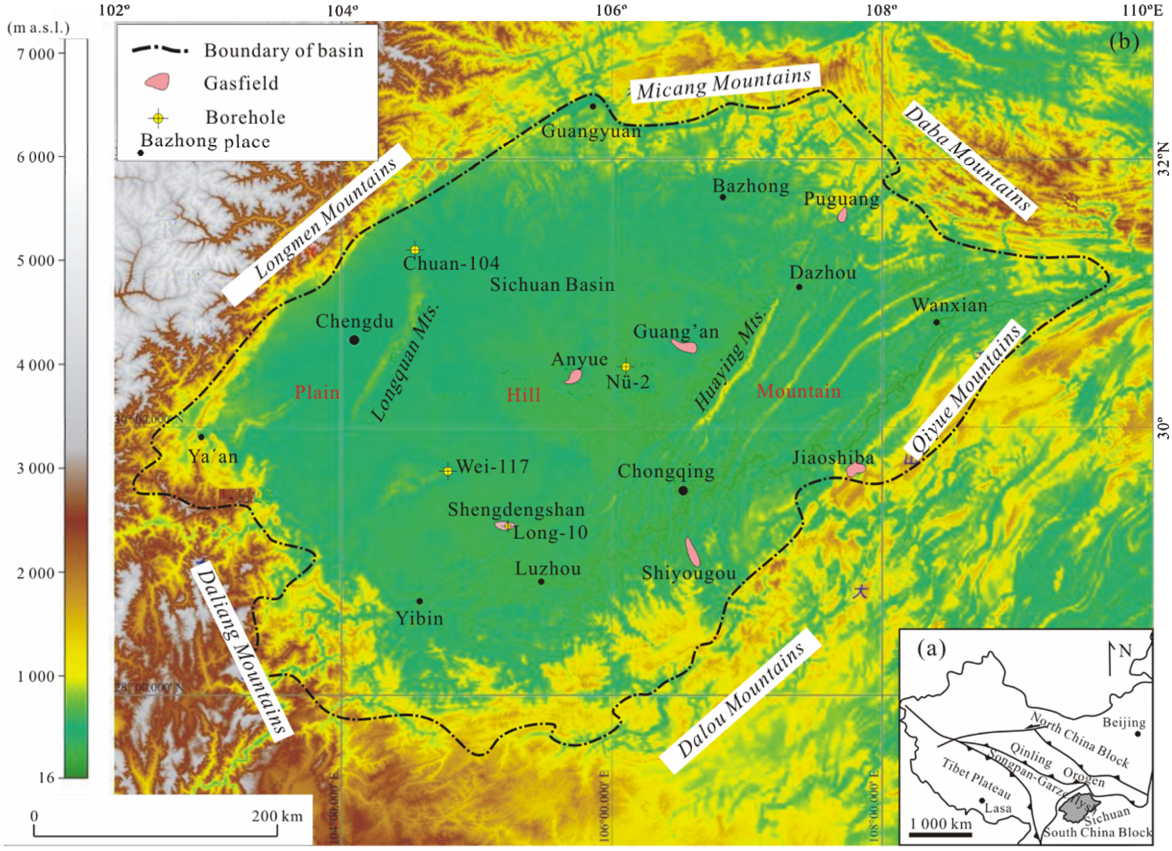

Figure 1. (a) Inser-map of the basic tectonic framework of the Sichuan Basin. (b) The digital elevation map (DEM) showing the topography and structure in the Sichuan Basin and its surroundings, which could be could be divided into three-part subdivision, i.e., the Chengdu Plain, central hill and mountains in eastern basin.

control the framework of the eastern Tibetan Plateau during post-Late-Triassic. It is thrusting with sinistral strike-slip which occurred during Late Triassic (Deng et al., 2012a; Chen and Wilson, 1996), reactivated under EW pressure during Cenozoic times (Wang and Burchfiel, 2000; Burchfiel et al., 1995). The reactivation of old structures has been interpreted as result of Late Cenozoic eastward, or southeastward extrusion of crustal material from the Tibetan Plateau (Wilson and Fowler, 2011; Burchfiel et al., 2008). Within the South China Block, Sichuan Basin is separated from a 1 300-km-wide Mesozoic intracontinental orogenic belt by the Qiyueshan-Daloushan structure (Li et al., 2012, 2007). It underwent a complicated tectono-magmatic evolution during the Late Mesozoic, referred to as the Yanshanian intracontiental orogeny (Li et al., 2007; Yan et al., 2003).

The Kongling complex with Archean age crystalline basement of the South China Block, overlain the Neoproterozoic Banxi Group. The latter represents folded basement, consisting of tightly folded, but only weakly metamorphosed greywacke-slate succession (BGMPSP, 1991). These basement rocks exposed around the Yangtze Platform (Fig. 2), are overlain by up to 10 km of Neoproterozoic (Ediacaran)–Phanerozoic strata. The sedimentary cover is comprised mainly of Paleozoic and Middle Mesozoic strata of shallow-marine deposits, and post-Late Triassic strata of terrestrial deposits. Although there are widespread low-angle unconformities or para-conformities, most of the Upper Silurian, Devonian and Carboniferous strata are absent due to Caledonian movement across the South China Block. The Upper Triassic, Jurassic, Cretaceous and Cenozoic strata are composed entirely of continental clastic sequences.

2 MORPHOLOGIC AND GEOLOGICAL CHARACTERISITCS OF THE SICHUAN BASIN

2.1 Morphologic Features and Three Part Subdivision of the Basin

The modern surface elevations of the basin vary from 400 to 1 000 m above sea level. It is surrounded by peripheral mountains with elevations of 1 500–4 000 m above sea level (Fig. 1). Within the basin the Longquan Mts. and Huaying Mts. divide it into three morphologically different areas. The plain area (Chengdu Plain) located west of the Longquan Mts. covers ~80 000 km^2 and has elevation of ~450–650 m above sea level, decreasing from northwest to southeast. Chengdu Plain is covered by Quaternary sedimentary deposits <500 m thick (BGMRSP, 1991). The hill area located between Longquan Mts. and Huaying Mts. has elevated ~300–550 m above sea level, decreasing from north to south, where the hills subtly grade into the Chengdu Plain. It exposes Jurassic–Cretaceous red beds in nearly horizontal strata over an area of ~120 000 km^2. The mountainous area to the east of Huaying Mts. has variable elevation of ~350–1 000 m and covers ~100 000 km^2. It is composed of a series of NE-striking anticlines and synclines. The anticlines, in which the Permian–Triassic strata outcrop, are narrow and steep. Most summits are of ~700–1 000 m in elevation, with peak elevations of ~1 700 m in the Huaying Mts. In contrast, the synclines show gentle to moderate deformation, where Jurassic strata outcrop at an average elevation of ~400 m.

2.2 Deformational Features and Three Part Subdivision of the Basin

The Sichuan Basin shows complicated tectonic structures (Fig. 2), indicative of multiple-stage and multi-directional shortening and extension from its complex tectonic history during the Phanerozoic. The basin can be divided into three belts with different deformation features, separated along the Leshan-Longquan Mts.-Langzhong-Nanjiang, and Yibin-Huaying Mts.-Dazhou (Fig. 3).

The western area of the Sichuan Basin, located between Longquan Mts. and Longmen Mts., is dominated by an Indosinian-Yanshanian thrust-belt and foreland basin (Deng et al., 2012a; Liu S G et al., 2012, 2005), most with NE-striking structural direction. However, under the influence of the Micang Mts., the northern segment is characterized by nearly EW and NE striking composite structures (e.g., Mianyang en-echelon structure). To the southwest of the western corner of the basin, the deformation is affected by growth of the Tibetan Plateau (Deng et al., 2012b; Hubbard and Shaw, 2009; Burchfiel et al., 2008), indicated by the occurrence of superimposed NS striking structures during Late Cenozoic times.

The central area of the Sichuan Basin, located between Longquan Mts.-Nanjiang and Yibin-Huaying Mts.-Dazhou, predominantly shows composite structures, striking NE and NW. These structures are generally characterized by gentle deformation and low-angle strata inclination in the outcrops. The curving fold structures in the northern part of the Sichuan Basin (e.g., Bazhong and Langzhong structures), are the result of subtle superimposition of multi-direction structures (Yue et al., 1996; BGMRSP, 1991). Toward the basin center, the influence of peripheral orogen decreases, EW striking structures dominate in the center of the basin, represented by the Nanchong-Suining area.

The eastern Sichuan Basin, located between the Yibin-Huaying Mts.-Dazhou and Qiyue Mts., is characterized by the development of NE-trending chevron anticlines, gentle synclines and northwestward thrust faults (Fig. 3). However, the fold axes shift from EW to NE, then to N (Fig. 2). It has been suggested that these tectonic changes are a result of progressive northwestward propagation of the Yanshanian intra-continental deformation in South China (Wang Z S et al., 2010; Jin C et al., 2009; Yan D P et al., 2009) and of the southwestward thrust-nappe tectonics from Dabashan intra-continental deformation (Shi et al., 2012). To the southern margin of the basin a triangular region located west of Chongqing and southeast of Yibin, shows composite NE, EW and SN striking structures during the Cretaceous to Cenozoic Period controlled by the Xuefeng Orogen, and the Tibetan Plateau (Deng et al., 2016; Yue et al., 1996).

2.3 Basement Features and Three Part Subdivision of the Basin

The Precambrian basement of the Sichuan Basin is composed of two units—the crystalline basement comprised by the

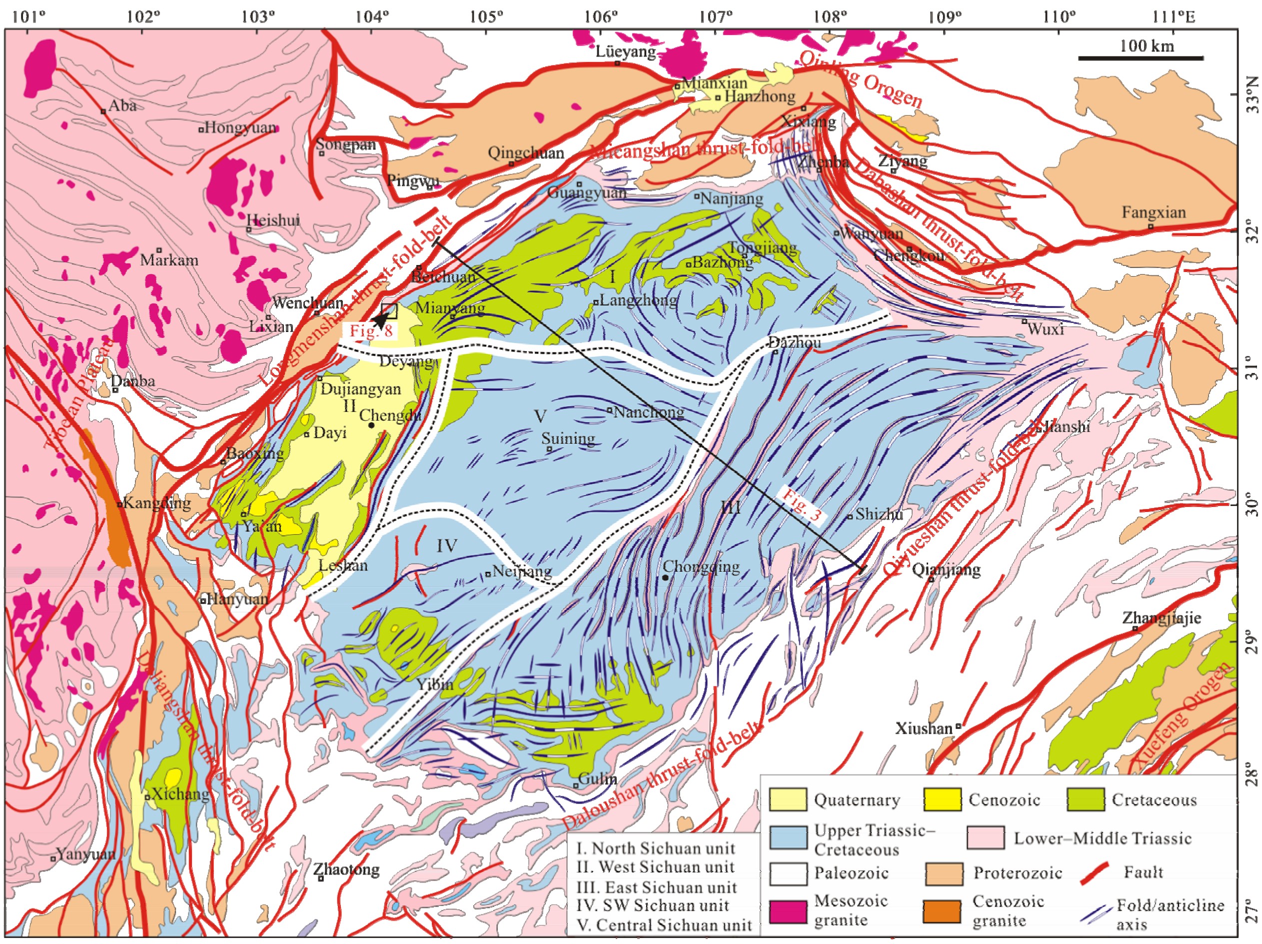

Figure 2. Structural features and division of the Sichuan Basin.

Archean–Paleoproterozoic Kangding Group, and the folded basement represented by the Meso-Proterozoic Huangshuihe and Neoproterozoic Banxi Group (Zheng et al., 2006; Luo, 1998; Guo et al., 1996; Luo et al., 1994; BGMRSP, 1991). The basement is cut by major boundary faults which divided the basin into three regions (Fig. 4), namely, the western, central and eastern regions. The most important faults are the NE-striking Longmenshan, Longquan, Huaying and Qiyue faults.

The three basement regions differ in lithology and structural deformation. The central basement region contains the Paleoproterozoic Kangding Group and Archean basic-ultra basic rocks. However, the western and eastern regions contain both the crystalline and the folded basements. The western region contains metamorphosed volcanic and sedimentary rocks of Mesoproterozoic age, whereas the eastern region is dominated by the Neoproterozoic metamorphic Banxi Group. Both of them were formed during the Neoproterozoic Jinning Period (0.8–1.0 billion years ago) (Zheng et al., 2006; BGMRSP, 1991).

The three parts subdivision of the basement features shows correlation with the three part subdivision of the morphologic and deformational features in the overlay cover mentioned previously. This indicates that the basement has profound influence on the basin development.

2.4 Basin Margins and Subdivision

The western and northern borders of the Sichuan Basin represent the western margin of the South China Block (Figs. 1, 3). These parts of the basin margin are comprised by large-scale thrust belts and foreland basins (Deng et al., 2012a; Liu S G et al., 2006, 2005, 1996; Li et al., 2003; Chen and Wilson, 1996). There are deep lithospheric structures (Robert et al., 2010; Jiang and Jin, 2005; Cheng et al., 2003) corresponding to the large and sharp contrast in present morphology between the basin and the adjacent mountains (Liu et al., 2012; Clark et al., 2004). The location of the boundary between foreland basins and the adjacent mountains is chiefly controlled by the changes of the deep lithospheric structure. In contrast, the eastern and southern margins of the Sichuan Basin are located within the South China Block.

There are similar lithospheric structures and gradual boundaries between the basin and the adjacent mountains (Wang Z X et al., 2010; Zhou et al., 1997; Wang, 1994; BGMRSP, 1991). The Sichuan Basin and the bordering mountains here are linked by

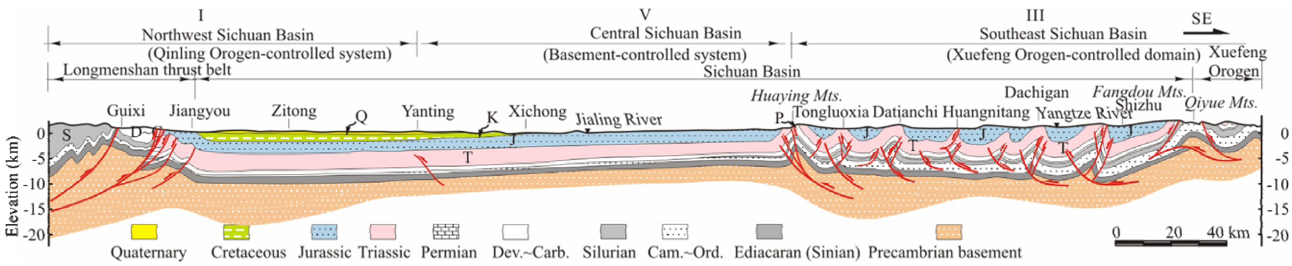

Figure 3. Simplified structural profile from NW to SE (Jiangyou-Xichong-Shizhu) across the Sichuan Basin (location shown in Fig. 2).

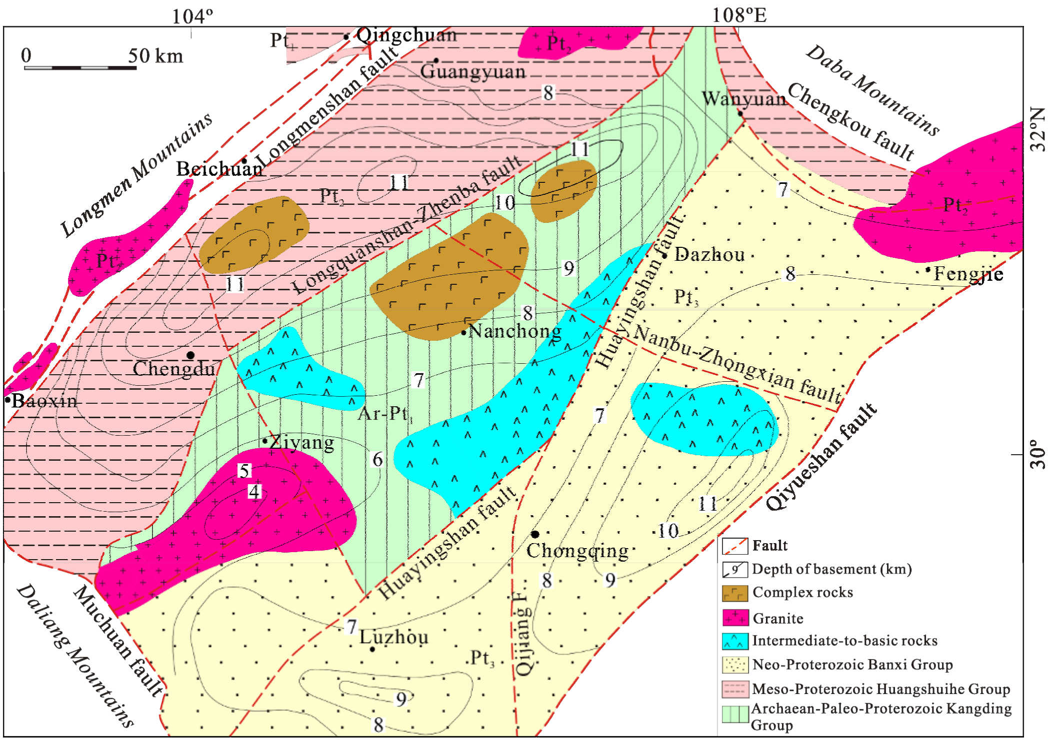

Figure 4. Basement features of the Sichuan Basin (modified after Luo, 1998), it suggests that the basement could be divided into three-part subdivision.

multi-layer detachments in the sedimentary cover of the Sichuan Basin (Chen et al., 2011; Jin W Z et al., 2009; Yan D P et al., 2009), that probably accommodated much foreland basin sediments removed by later strong erosion as the Appalachian foreland basin in New York (Blackmer et al., 1994). Thus, under the influence of surrounding orogeny, the Sichuan Basin can be subdivided into five units (Table 2, Fig. 2).

Unit I—The North Sichuan unit (Tables 1, 2). The area is bordered by the Yingshan and Xinchang anticlines at the south (Fig. 2). The Indosinian-Yanshanian thrust-belt and foreland basin were controlled by the evolution of the Qinling Orogen and its multi-layered thrusting to the basin (Liu et al., 2012; Plesch et al., 2007; Wu et al., 2006). Unit II—The West Sichuan unit is affected by the evolution of the Tibetan Plateau and its multi-layered thrusting to the basin (Deng et al., 2012a; Hubbard and Shaw, 2009; Burchfiel et al., 2008).

Unit III—The East Sichuan unit is characterized by development of chevron anticlines, gentle synclines and significant multi-layered detachment along the Lower Triassic, Silurian and Lower Cambrian shale (Figs. 2, 3) (Yan D P et al., 2009,

Table 1 Characteristics of the basin margins in the Sichuan Basin

Types	Cases	Geomorphic features	Tectonic features	Formation time
Western and northern basin margins	Longmen Mts. and West Sichuan foreland basin	Large contrast in morphology between mountain and basin; extremely steep gradient and clear basin boundary	The deep lithospheric structure is diverse between Longmenshan thrust belt and west Sichuan foreland basin, with distinct zoning and layering features. The uplift and erosion in the mountain and subsidence in the basin are coupled	Himalayan (Tertary)
	Micang Mts. and North Sichuan foreland basin	Large contrast in morphology between mountain and basin; extremely steep gradient and clear basin boundary	The deep structure of lithosphere is diverse between the basin and the mountain. There is Micangshan thrust belt and north Sichuan foreland basin, with distinct zoning and layering features	Mid–Late Yanshanian (Jurassic Period)
	Daba Mts. and Northeast Sichuan foreland basin	Large contrast in morphology between mountain and basin; extremely steep gradient and clear basin boundary	The structure of the lithosphere is diverse between the basin and the mountain. There is Dabashan thrust belt and northeast Sichuan foreland basin, with distinct zoning and layering. The uplift and erosion in the mountain and subsidence in the basin are coupled	Late Yanshanian (Cretaceous Period)
Southern and eastern basin margins	Qiyue Mts. and East Sichuan Basin	Slight contrast in morphology between mountain and basin; obscure basin boundary; lack of steep variation between the fold belt and the front of the mountain	The deep structure of the lithosphere is similar, controlled by the northwestward multi-layered detachment and compressional deformation within the South China Block. There are typical Jura-type folds in the structure	Late Yanshanian (Cretaceous Period)
	Dalou Mts. and South Sichuan Basin	Minimum contrast in the morphology between mountain and basin; obscure basin boundary; lack of steep variation between the folded belt and the front of the mountain	The deep structure of the lithosphere is similar between the basin and the mountain, controlled by the northwestward multi-layered detachment and compressional deformation of Xuefeng Orogen. There are typical Jura-type folds	Late Yanshanian–Early Himalayan (Cretaceous Period to Tertary Period)
	Daliang Mts. and Southwest Sichuan Basin	Slight contrast in morphology between mountain and basin; obscure basin boundary; lack of steep variation between the folded belt and the front of the mountain	The deep structure of the lithosphere is similar between the basin and the mountain, controlled by transpression on the southwestern margin of the South China Block	Himalayan (Quarternary Period)

Table 2 Features of the different units in the basin-mountain tectonic systems

Units	Structural features	Dynamics
I. North Sichuan unit	Comprised by Daba thrust belt, Micang thrust belt, North Longmen thrust belt and North Sichuan foreland basin; the structure in the basin predominantly parallel to the strike of the thrust-belt. The deformation significantly weakens from the thrust belts to the basin	Controlled by the evolution of Qinling Orogen and its multi-stage thrusting to the basin
II. West Sichuan unit	Consisting of the central and southern segments of Longmen Mts. and West Sichuan foreland basin. The deformation significantly weakens from the thrusting to the basin center, with the NE and N-S striking structure	Controlled by the evolution of Tibetan Plateau and its multi-stage thrusting to the basin
III. East Sichuan unit	NE-striking chevron anticlines, gentle synclines with much stronger deformation in the northern segment	Controlled by intra-continental deformation from Xuefeng Orogen and its multi-layered detachment to the basin
IV. Southwest Sichuan unit	The deformation weakens from Daliang Mts. To the basin, characteristic of gentle composite structures with NE and NW strike	Controlled by intra-continental deformation from Xuefeng Orogen, the evolution of Tibetan Plateau and basement structures
V. Central Sichuan unit	Insignificant influence from surrounding mountains. It is located at the rigid basement in the center of the Sichuan Basin. The structure is characteristic by gentle deformation, with nearly E-W strike, southwestward changing to an echelon NE-striking structure	Controlled by the basement lithology and structures

2003), controlled by northwestward deformation of the Xuefeng Orogen during the Cretaceous Period (Jin et al., 2009; Yan D P et al., 2009, 2003). Unit IV—The Southwest Sichuan unit is characterized by gentle structures (anticline and syncline) and southwestward increasing deformation (Chen et al., 2011; Wang and Yin, 2009), which is controlled by the Xuefeng Orogen, and the Tibetan Plateau (Deng et al., 2016; Chen et al., 2011; Wang and Liu, 2009). Unit V—The Central Sichuan unit is characterized by gentle deformation with near EW strike, indicative of insignificant influence from the surrounding mountains (Zhang et al., 2011; Plesch et al., 2007). The deformation is predominantly controlled by the basement lithology and structures.

3 MULTI-STAGE EVOLUTION OF THE SICHUAN BASIN

3.1 Three Major Episodes of the Basin Evolution Process

3.1.1 Marine carbonate platform ($Z–T_3^1$)

The multi-stage tectonic evolutionary process of the Sichuan Basin can be divided into three episodes based on the stratigraphy and petrology, as well as tectonic movement etc. (Fig. 5, Table 3). The first episode of the Sichuan Basin evolution is dominated by carbonate platform development, which began during the Ediacaran epoch and lasted until early Late Triassic time ($Z–T_3^1$). Sediment deposition was mainly occurring under a divergent plate tectonic setting. During this long period of cratonic and passive margin evolution, >5 km thick sedimentary strata were deposited in shallow marine and tidal flat carbonate environments (Guo, 2013; Guo et al., 1996). The deposition was influenced in particular by two extensional tectonic episodes, i.e., the Xingkai and Emeishan movement (Luo et al., 2001), which resulted in the formation of the Early Cambrian Mianyang-Changning and Late Permian Kaijiang-Liangping intracratonic sags (Liu et al., 2013a) followed the term of "intracratonic sag" by Allen and Allen (2013), defined such structures characterized with long-lived extensional strain and no distinct offset of extensional fault. In those basins accumulated significant deposits of black mudstone, future source rocks for petroleum (Fig. 6). Both of these intracratonic sags had major influence on the petroleum potential across the Sichuan Basin, e.g., the source rock quality and reservoir properties. The petroleum accumulated preferably at the periphery of these intracratonic sags due to high-effectiveness migration and high-quality reservoir (Liu et al., 2013a; Wang et al., 1998). The Late Permian Emeishan extensional movement accompanied by magmatic events had widespread influence on the thermal history of the petroleum systems, in particular around the southwestern margin of the basin.

3.1.2 Foreland basin ($T_3^2–K_2$)

Since Late Triassic the Sichuan Basin has experienced a significant transformation into a continental clastic foreland basin (units I and II). It indicates that a predominant period of tectonic change from divergent to convergent during this period, resulting in the Longmenshan, Micangshan and Dabashan thrust-fold-belts and related northwestern and northern Sichuan foreland basin (Deng et al., 2012a; Liu S G et al., 2005; Guo et al., 1996). There are >4 km terrestrial strata deposited in the basin, spanning in age from the Upper Triassic Xujiahe Formation up to the Quaternary (Liu et al., 2006; BGMRSP, 1991). Not only does the great thickness of T_3–K terrestrial strata serve as regional caps for the underlying marine petroleum systems, but also it built up continental clastic petroleum systems, particularly in the Late Triassic Xujiahe Formation (Fig. 5). Due to the predominant influence of the Tibetan Plateau in Late-Cretaceous to Cenozoic time (Hubbard and Shaw, 2009; Burchfiel et al., 2008, 1995; Jia et al., 2006), the latest thrusting and uplifting took place around the southwestern margin of the Sichuan Basin (units II and IV), with occurrence of a limited Late Cretaceous to Cenozoic foreland basin.

3.1.3 Uplift and exhumation (K_2–Q)

Significant uplift and exhumation occurred across the Sichuan Basin after Late Cretaceous (Deng et al., 2013a, b, 2009; Li Z W et al., 2012; Li J Z et al., 2009; Li W et al., 2009; Shen et al., 2009; Liu et al., 2008b; Richardson et al., 2008) with an

Table 3 The three-episodes of the evolution in the Sichuan Basin during Phanerozoic

Phase	Structural features	Implications for petroleum accumulation
Uplift and exhumation (E_2–Q)	Basin-scale uplift and exhumation, resulting in extensive erosion of the Upper Jurassic–Cretaceous strata, and final building up of the present framework of the basin	Building up structural traps and reform the previous lithologic traps. Significant adjustment of energy field in the basin, cross-formation migration of fluid, rapid accumulation of natural gas. In particular, the preservation condition of the eastern and margin of the basin was greatly damaged
Foreland basin ($T_3^2–E_2$)	Predominant Period of building up the structural framework of the Sichuan Basin, with thrust-belt and foreland basin. The major tectonic change from extension to compression formed a rhomboid-shaped foreland basin	Building up continental clastic petroleum systems. Great thick T_3–K terrestrial strata can serve as regional caps for buried marine petroleum systems dominant with structural and lithologic paleo-gas-pools, with high- to over-maturity of source rocks
Marine carbonate platform ($Z–T_3^1$)	Multi-stage extensional tectonics, e.g., Xingkai and Emeishan movement, and contraction deformation, e.g., Chengjiang and Yunnan movement. Significant deposits of black, organic carbon rich mudstone in the Lower Cambrian and Silurian, dominated by carbonate platform deposition. Extensive erosion from Late Silurian to Carboniferous across the basin	Significantly building up marine petroleum systems dominant with structural and lithologic paleo-oil-pools, with highly matured marine source rocks. The Xingkai and Emeishan movement have accommodated widespread influence on the thermal history of petroleum systems, in particular, around the central and southwestern parts of the basin

increase in erosion rate during Late Cenozoic (Fig. 7). It probably signifies the co-influence of Late Cretaceous tectonic change in basin geodynamics (Deng et al., 2012b), and the influence of Tibetan Plateau growth.

Based on the modeled temperature-time histories of thermal properties in the Sichuan Basin (surface temperature of 10–20 °C, geothermal gradient of 20–30 °C/km), the cooling and exhumation process across the basin can be divided into three stages (Fig. 7). The first stage is characterized by differential cooling and exhumation with various rates across the basin, from the Late Cretaceous to Paleogene. During the second stage a slow rate of exhumation occurred across the basin through the Early Neogene. It was followed by a Late Cenozoic significant increase (the third stage) across the basin. The rate and magnitude of exhumation were ~40 m/Ma and ~1 000 m during the first stage, ~100 m/Ma and ~1 500 m in the second and third stage (Deng et al., 2013b, 2009; Liu et al., 2008b), respectively. The significant exhumation across the Sichuan Basin resulted in extensive erosion of the Upper Jurassic–Cretaceous strata and final building of the present framework of the basin, which could be resulted from the reorganization of Yangtze River or a base-level falling (Richardson et al., 2008; Clark et al., 2004) although the reorganization processes has been strongly debated (Richardson et al., 2008; Zheng et al., 2006). The western and northern Sichuan Basin (units I and II) were subjected to relatively weak denudation since the Late Cretaceous, as well as the central Sichuan Basin (Unit V) (Deng et al., 2013a, b, 2009; Shen et al., 2009; Liu et al., 2008b; Richardson et al., 2008). Based on more than 100 apatite fission track samples and vitrinite data across the basin, it suggests that the magnitude of the erosion is less than 3 000 m at (units I, II and V) (Deng et al., 2013b, 2009; Liu et al., 2012) in contrast to the eastern Sichuan Basin (Unit III) with the magnitude of more than 3 500 m. It should be noted that there has been significant change in the exhumation (at least ~2 000 m) across the Huaying Mts. (Deng et al., 2013b). Such a substantial uplift and exhumation accommodated significant change and adjust of the gas accumulation across the Sichuan Basin, e.g., the Weiyuan Gasfield (Liu et al., 2015a, b, 2008b).

3.2 Tectonically Driven Sedimentary Changes during Mesozoic–Cenozoic

During Mesozoic–Cenozoic time, the Sichuan Basin has experienced three episodes of tectonically driven sedimentary changes (Fig. 5, Table 3). The first tectonically driven change

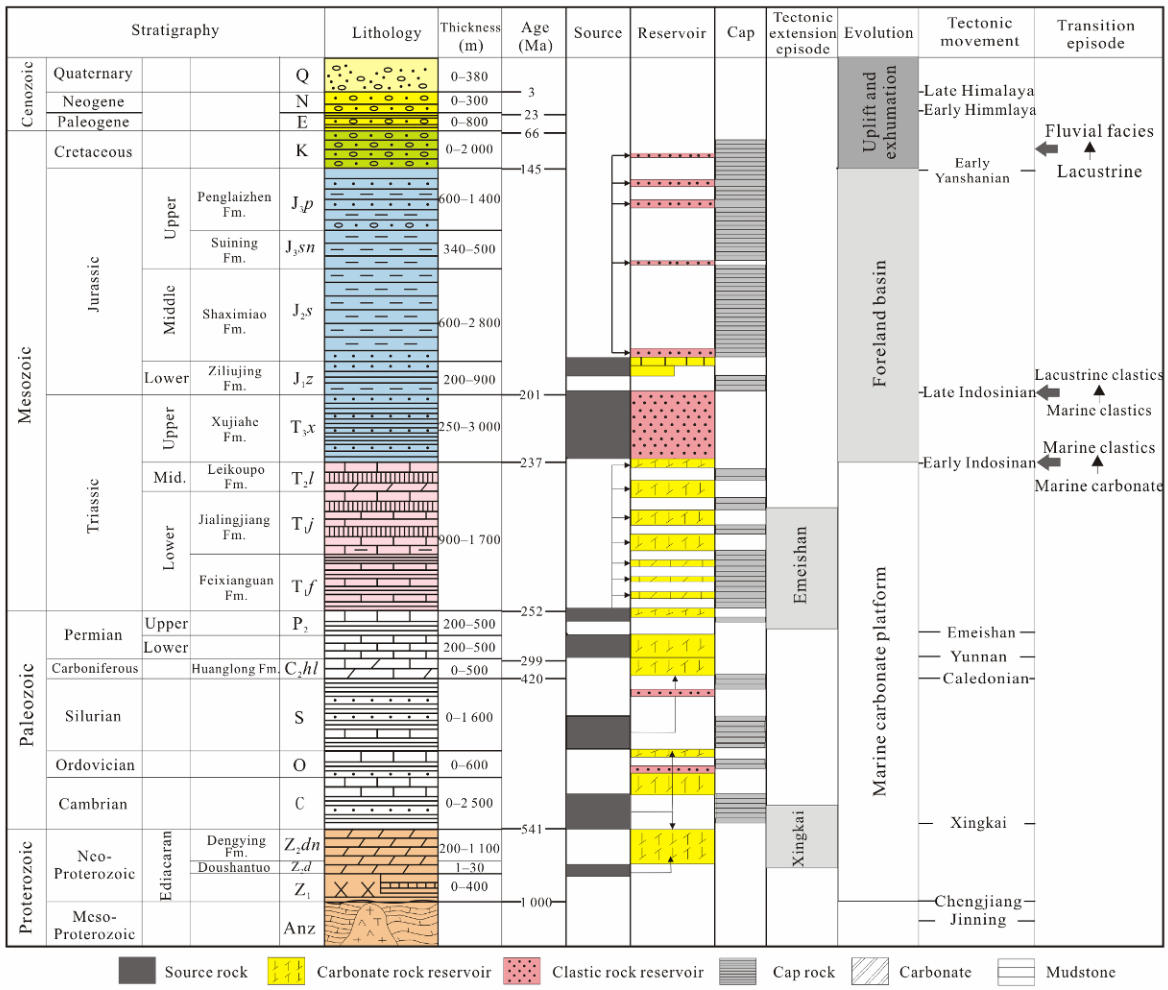

Figure 5. Stratigraphy, tectonic evolution and source-reservoir-cap rocks in the Sichuan Basin, indicating of multi-stage evolution and hydrocarbon accumulation across the basin.

from marine carbonate platform to marine clastic facies occurred during the Carnian, as indicated by the disappearance of the Maantang reefs (T_3m) and by the increase of terrigenous clastics influx (Yang et al., 2010; Liu et al., 2009a; Wu, 1989). This process ended the long period of the craton and passive margin stage (Ediacaran to Late Triassic, Z_2–T_3^1), which was dominated by carbonate platforms and extensional tectonics. The lower part of the Maantang Formation is comprised by oolitic and reef limestones, with clastics being rare. However, clastics and bioclasts increase within micritic limestone in the upper part of the Maantang Formation (Fig. 8). The terrigenous clastics deposition in the Xiaotangzi Formation (T_3t) culminates in the deposition of muddy siltstone, while reefs finally disappeared, and marine clastic facies prevailed. The second transformation is from marine clastic facies to terrestrial lacustrine clastic facies. It is the result of transpressional deformation occurring during Late Triassic time in western Sichuan (units I and II) and directed from the northeast to the southwest (Liu et al., 2013b, 2009b; Deng et al., 2012a; Deng, 2007). In particular, the sedimentary data indicate that marine delta deposits were widespread in the southwestern Sichuan Basin (units II and IV) (e.g., Anyue area, Zhao X F et al., 2008),

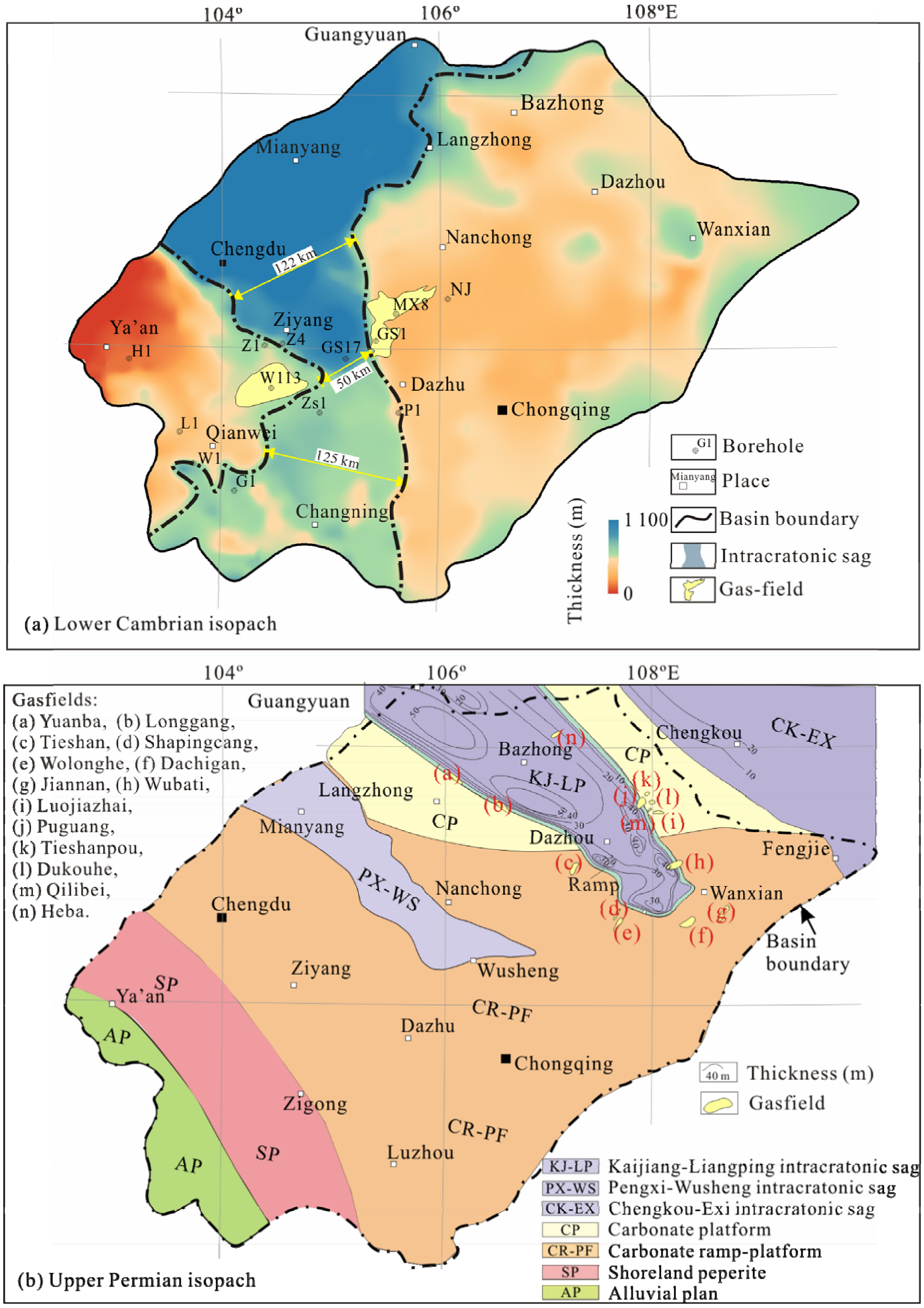

Figure 6. Geological maps of two intracratonic sags and of main gasfields across the Sichuan Basin. (a) Early Cambrian Mianyang-Changning intracratonic sag indicated by the much thickness of Lower Cambrian strata, (b) Late Permian Kaijiang-Liangping intracratonic sag (modified after Wang et al., 2002), it is consistent with the occurrence of deep-water deposits during Late Permian times.

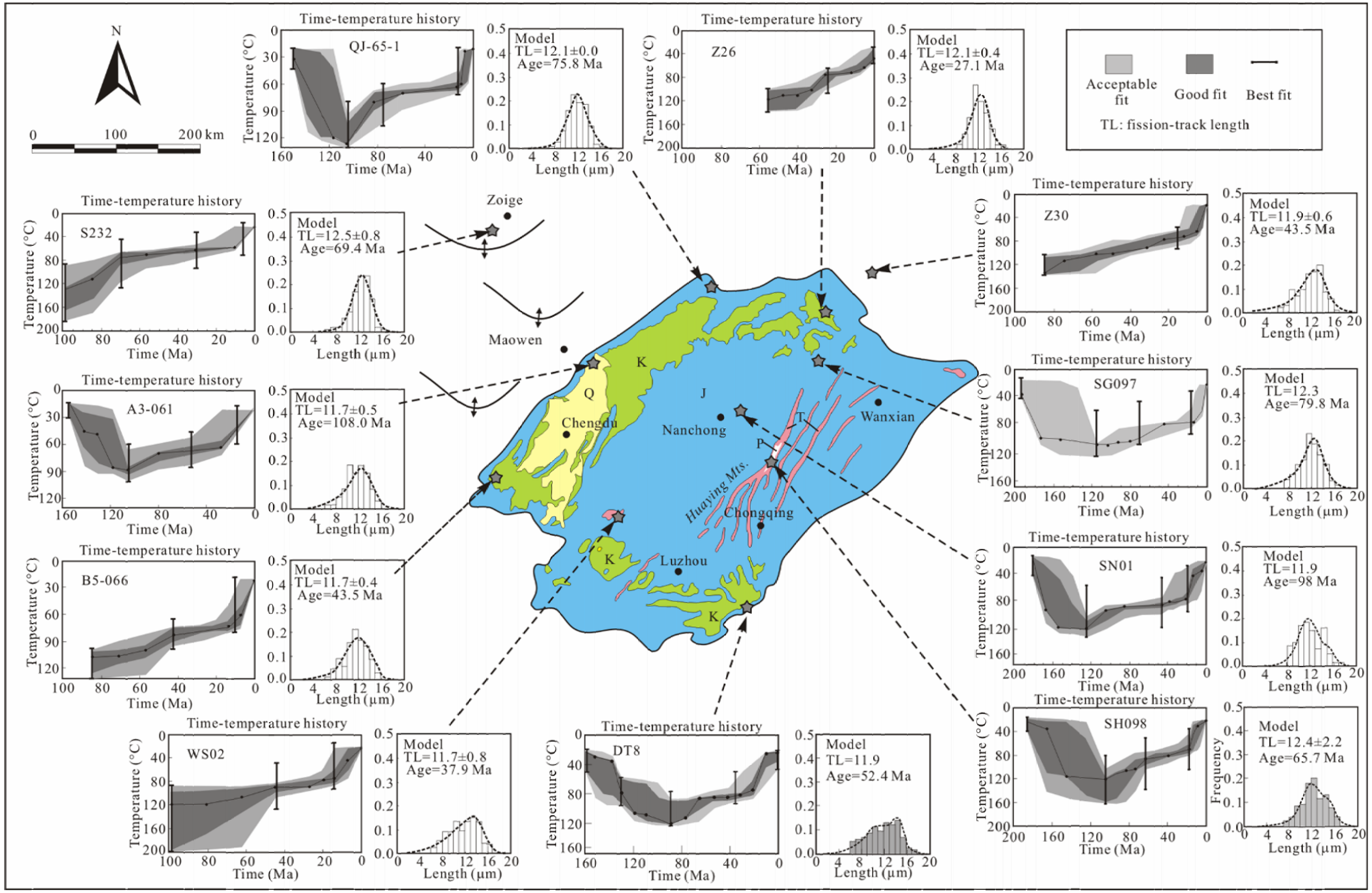

Figure 7. Post-Early-Cretaceous episodic cooling and exhumation processes across the Sichuan Basin, indicated by modeled cooling histories for selected representative samples from the inversion of AFT (apatite fission track) age and length distribution (modified from Deng et al., 2013b, 2009; Li et al., 2012; Liu et al., 2008b). All samples are from Late Triassic–Early Cretaceous terrestrial strata, indicating of three episodes of cooling and exhumation from about 100 Ma.

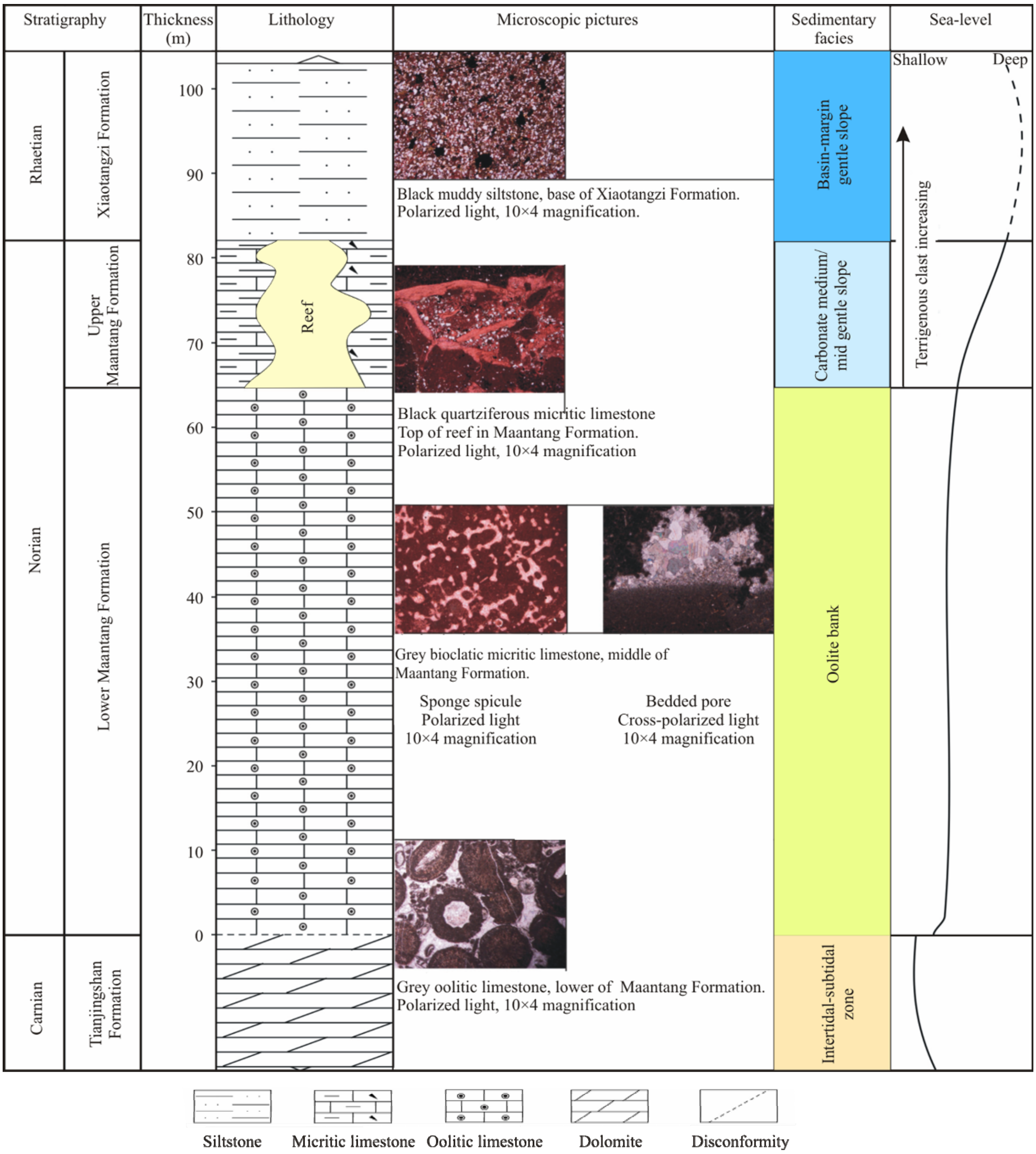

Figure 8. Rhaetian-Norian transition from marine carbonate facies to marine clastic facies at the western Sichuan Basin (see location in Fig. 2).

where they are represented by the lower part of the Upper Triassic Xujiahe Formation. Thus, we suggest that the tectonically driven change from marine clastic facies to terrestrial lacustrine clastic facies occurred after Rhaetian-Norian time across the western Sichuan Basin (units I, II and IV), progressing from the northeast to the southwest. Until the end of the Late Triassic, the Sichuan Basin was transformed into a terrestrial basin, predominantly filled by lacustrine clastics. Lacustrine and fluvial facies dominated during Jurassic–Cretaceous time in the basin. Based on the similarity in paleontology, lithology and sedimentary facies across the region (Guo et al., 1996; Xia, 1982), it can be suggested that paleo-lacustrine environments prevailed in the Sichuan, Xichang, and Yunnan basins and much of the Huibei area, all located on the western margin of the South China Block (Guo et al., 1996).

From the Late Cretaceous on, the Sichuan Basin has progressively undergone another tectonic change, causing shrinking of the earlier paleo-lacustrine environment. This was a result of differential exhumation across the basin. The Late Cretaceous tectonic change is indicated by: (a) significant exhumation beginning at this time as demonstrated by thermal modeling of apatite fission tracks across the basin and its periphery from Late Triassic to Early Cretaceous terrestrial strata (Deng et al., 2013a, 2009; Li et al., 2012; Wilson and Fowler, 2011; Shen et al., 2009; Enkelmann et al., 2006; Reiners et al., 2003); (b) significant exhumation around the northern and eastern part of the basin, whereas high subsidence and deposition took place around the southern and western part of the basin, where >2 000 m thick sediments were deposited (Fig. 9); (c) tectonic change of basin geodynamics from the Qinling

Orogen to the Tibetan Plateau (Deng et al., 2012b).

Thus, the Late Cretaceous–Eocene strata only outcrop near the southwestern boundary of the Sichuan Basin (units III and IV), demonstrating that the paleo-lacustrine environment was shrinking southwestward. The Cenozoic build-up of Daliang Mts. and significant sinistral movement at the boundary faults (e.g., the Xianshuihe and Xiaojiang faults) occurred around the southwestern margin of the Sichuan Basin (Chen et al., 2011; Deng et al., 2011; Wang and Yin, 2009; Wang and Burchfiel, 2000). It led to constriction of the paleo-lacustrine environments. By the Eocene, the depositional environment within the Sichuan Basin had become restricted, with deposition of evaporites-gypsum, salt and mirabilite (e.g., the Shuangliu and Minshan areas at the Unit III, Guo et al., 1996). During this time, the Sichuan Basin became an internally drained basin. In particular, rapid exhumation took place (ca. 40–20 Ma) across the Sichuan Basin (Fig. 7). Thus, we suggest that the third tectonic change occurred across the Sichuan Basin in Eocene time, as indicated by disappearing paleo-lacustrine environments, and basin-scale differential exhumation.

4 HYDROCARBON GEOLOGY AND ACCUMULATIONS IN THE SICHUAN BASIN

The Sichuan Basin is one of the biggest petroliferous basins in China. More than 175 gasfields and 13 oilfields had been discovered by the end of 2015. Most of the petroleum resources in the Sichuan Basin are thermogenic gas, which derived from oil mostly sourced from marine carbonate rocks. The oils cracked into gases when exposed to higher temperatures. Besides that, some of the gas is generated from gas-prone type III kerogen in the terrestrial strata (Zhao et al., 2010; Liu et al., 2008a; Tian et al., 2008). The total proven hydrocarbon in-place reserves in the basin were up to 2.6×10^{12} m^3, of which 85.05% were sourced from marine organic matter and 14.95% were from terrestrial organic matter (Table 4). The latest resource assessment in 2002 (Wang et al., 2005) indicated that the total amount of conventional prospective petroleum geological resources are up to 4.26×10^8 t (oil) and 5.35×10^{12} m^3 (gas). Furthermore, Li J Z et al. (2009) and Yan C Z et al (2009) suggested the inferred unconventional petroleum geological resources are 7.14×10^{12}–14.6×10^{12} and 2×10^{12}–4×10^{12} m^3 in the Cambrian and Silurian shales, respectively. OGCGS (2013) suggest that the geological resource of shale-gas is about ca. 40×10^{12} m^3 in the Sichuan Basin and its periphery. The statistics data for proven gas resources at the end of 2013 is given in Table 5. The main reasons for the abundant hydrocarbon accumulations in the Sichuan Basin are abundant organic matter, deep burial and good sealing conditions (Liu et al., 2015b, 2008a).

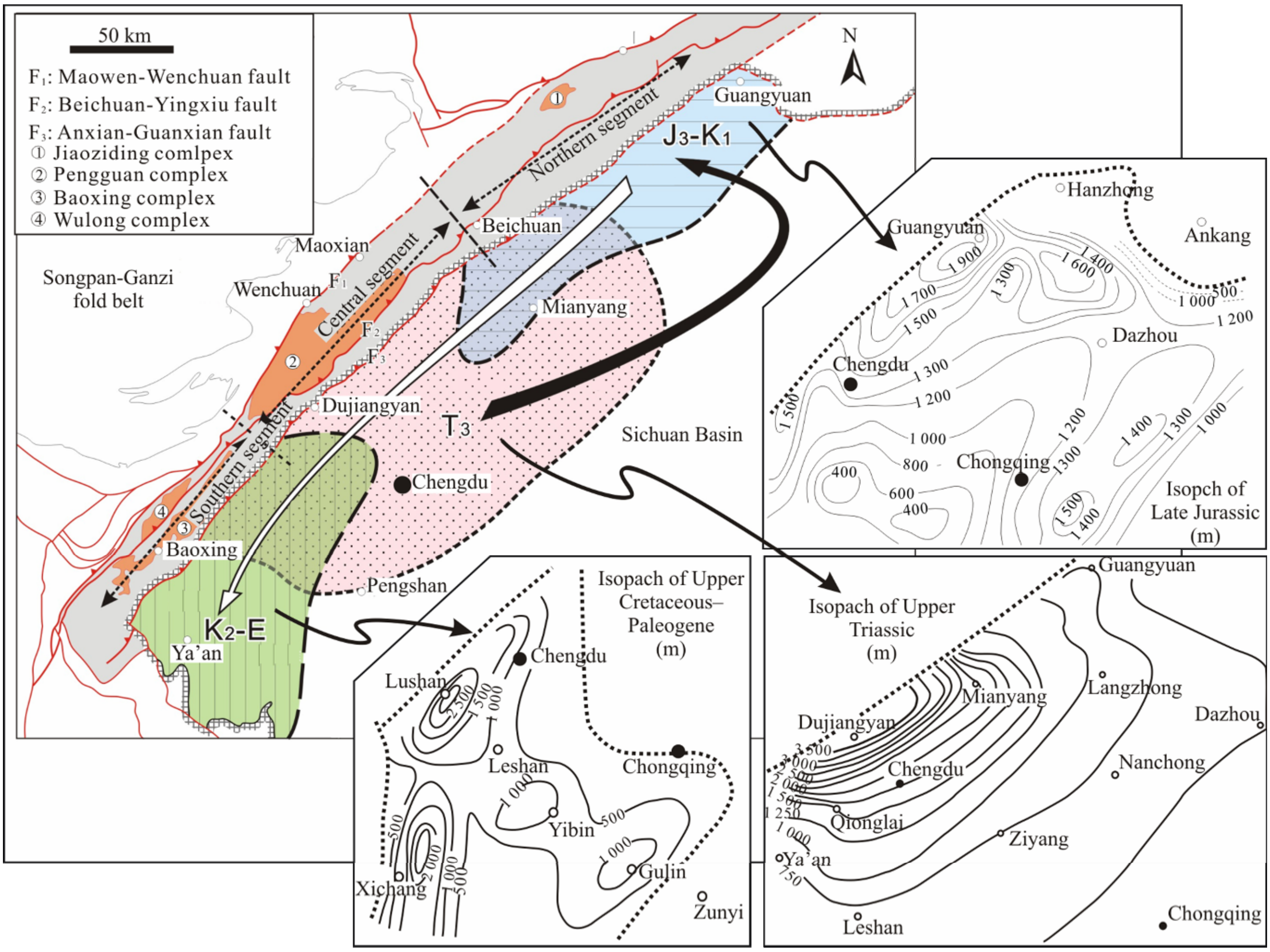

Figure 9. Foredeeps migration during the Mesozoic time in the Sichuan Basin, indicating of a southwestern propagation of foredeeps, isopach are modified from BGMRSP (1991), Guo et al. (1996) and Liu S F et al. (2005).

4.1 Source Rocks

There are five sets of source rocks for hydrocarbon generation across the Sichuan Basin, namely Lower Cambiran Qiongzhusi Formation (ϵ_1q), Lower Silurian Longmaxi Formation (S_1l), Upper Permian Longtan and Changxing formations (P_3), Upper Triassic Xujiahe Formation (T_3x) and Lower Jurassic Da'anzai-Lianggaoshan formations (J_1). The Xujiahe Formation (T_3x) contains gas-prone Type III kerogen, the Longtan and Changxing formations (P_3) are dominated by gas-prone type III and oil-prone Type II kerogen (Table 5). The other formations are dominated by oil-prone Type II kerogen. The cumulative thickness of all source-rock sequences in the basin is ca. 1 500–2 500 m (Huang, 1998; Guo et al., 1996).

The source rocks are rich in organic carbon, show high intensity of hydrocarbon generation and high thermal maturity (Table 5). The deep burial and high temperatures resulted in an increase in thermal maturity of the source rocks and transformation of oil to gas. Even the youngest source rocks of the Da'anzai-Lianggaoshan formations (J_1) where the *Ro* is 1.1%–1.9% indicate that hydrocarbon generation is spanning from oil to condensates. Deep burial has resulted in the thermal cracking of oil and bitumen to gas, particularly in the Lower Cambrian and Lower Silurian source rocks. The predominant oil-generation of Paleozoic source rock occurred before the Middle Triassic, thus most of paleo-uplift across the Sichuan Basin are widespread with bitumen, indicating of occurrence of oil-accumulation both in present gasfields and destroyed paleo-oil pools, e.g., the Dingshan-Lintanchang paleo-oil pool and the Puguang Gasfield (Liu et al., 2009c; Tian et al., 2008; Ma et al., 2007). However, the subsequent oil-cracked gas period and gas-generation of Permian to Late Triassic to source rock dominantly took place during the Indosinian-Yanshanian times, coevally with building of northern and western foreland basins and related thrust-fold-belt (units I, II and IV) (Deng et al., 2012b; Liu S G et al., 2012, 2006; Dong et al., 2008; Li et al., 2007; Liu S F et al., 2005). Thus, the sealing conditions are crucial for final gas remigration and accumulation across the Sichuan Basin.

Table 4 Statistics of proven gas reserves in Sichuan Basin (by the end of 2014)

Units	Strata	A ($\times10^8$ m^3)	B ($\times10^8$ m^3)	C ($\times10^8$ m^3)	D ($\times10^8$ m^3)	Total ($\times10^8$ m^3)	Percentage (%)	
Upper unit	J, E–N	7.71	15.18			22.89	0.09	14.95
	J, K		175.58			175.58	0.67	
	J	314.89	607.97			915.15	3.49	
	J, T	674.32	2 132.31			2 806.63	10.71	
Middle unit	T	6 845.24	10.16	191.56		7 046.96	26.88	66.69
	P, T	2 530.79	34.75	4 121.73	159.91	6 847.18	26.12	
	P	131.08				131.08	0.50	
	C, P	83.99				83.99	0.32	
	C	522.59				522.59	1.99	
	C, P, T	2 742.5				2 742.5	10.46	
	C, T	110.59				110.59	0.42	
Lower unit	P, Є, Z	4 812.4				4 812.4	18.36	18.36
	P, O	2.27				2.27	0.01	
	Total	18 768.38	2 977.95	4 313.29	159.91	26 217.54	100	
	Percentage (%)	71.59	11.35	16.45	0.61	100		

A is from the Southwest Oil/Gas Field Branch of CNPC; B is from the Southwest Oil/Gas Branch of SINOPEC; C is from the South Company of SINOPEC; D is from the Jianghan Company of Sinopec.

Table 5 Characteristics of major source rocks in the Sichuan Basin

Strata	Facies	Thickness (m)	C (%)	Kerogen type	Intensity of hydrocarbon generation ($\times10^4$ t/km^2)	Thermal maturity (*Ro*)	Oil/gas-generation period	Oil-cracked gas period
J_1	Continental	50–350	~0.96	I	~59	1.1–1.9	J_2–K	
T_3x	Continental	50–300	>1%–16.48%, mean ~2%,	III	~160	0.64–3.2, most<2.0	T_3–J_3	
P_3	Continental & marine	0–25	0.5%–12.55%, mean ~2.91%	I, III	~40	1.5–2.8	T_3–J_3	J_3–K
S_1l	Marine	0–650	0.1%–4.88%, mean ~1.1%	I	>125	>2.0	P–T_1	T_3–J_1
ϵ_1q	Marine	0–420	0.75%–1.5%	I	>200	>2.5	C–P_1	T–J_3

ϵ_1q. Lower Cambiran Qiongzhusi Formation; S_1l. Lower Silurian Longmaxi Formation; P_3. Upper Permian Longtan and Changxing formations; T_3x. Upper Triassic Xujiahe Formation; J_1. Lower Jurassic Da'anzai-Lianggaoshan formations; predominant oil-generation and oil-cracked gas periods are from Dong et al. (2015), Sun et al. (2011, 2007), Yang et al. (2005), and Huang et al. (1997).

4.2 Sealing Conditions

(1) Middle–Lower Triassic evaporites as regional caprock: At the end of the deposition of the Middle-Triassic Leikoupo Formation, the Sichuan Basin experienced widespread denudation, resulting in the erosion of up to the 3rd and 4th members of the Leikoupo Formation across the basin, except at the Luzhou and Kaijiang paleo-uplift, where substantial erosion reached up to the Lower Triassic Jialingjiang Formation.

However, the thick gypsum deposits located in the 2nd member of the Leikoupo and Jialingjiang formations probably experienced minor erosion across the basin, including the area of the paleo-uplift. In particular, according to the geochemical data, the fresh water at that time had not reached the seal of the 2nd member of the Leikoupo Formation. The gasfields underlying the Leikoupo Formation thus have favorable sealing conditions, e.g., the Moxi and Zhongba gasfields (Ma et al., 2010; Liu et al., 2008c; Zhang and Zhu, 2006). Furthermore, the total thickness of the Middle–Lower Triassic evaporitic seal is ~200 m across much of the Sichuan Basin (Fig. 10), and up to 300 m in the western and central parts of the basin (units I, II and V). Due to Cenozoic erosion, evaporites are only ~100 m thick in the south and east of the basin (units III and IV). Despite that, the Middle–Lower Triassic evaporites form a regional cap for the underlying marine reservoirs across the Sichuan Basin. According to the geochemistry data, there are two different fluid systems in the Sichuan Basin. The lower system is within Z_2–T_2l marine carbonates and the upper system within T_3–K clastic rocks (Fig. 11). Fluids (e.g., oil, gas, water) in the same system actively formed multi-source hydrocarbon pools, but rarely circulated between these two systems. One of the reasons is that the Middle–Lower Triassic evaporites in the Jialingjiang and Leikoupo formations provide efficient regional seals for a cross-systems circulation.

(2) The preservation condition for hydrocarbons: The tectonics exert a major influence on preservation conditions, chiefly through the influence on thickness of deposited terrestrial strata, intensity of deformation along the basin boundary, and magnitude of denudation. Good correlation in Sichuan Basins can be found between good preservation of the hydrocarbons in the terrestrial deposits and denudation (Fig. 12). At the western and northern part of the Sichuan Basin (units I and II), very thick terrestrial strata of more than 3 000 m were deposited since the Late Triassic (Liu et al., 2012; Li et al., 2003; Wang, 1996), with relatively weak denudation since the Late Cretaceous (Deng et al., 2013a, b, 2009; Liu et al., 2008b; Richardson et al., 2008). However, significantly thinner terrestrial strata (less than 1 500 m) were deposited in the southern and eastern parts of the Sichuan Basin (units III and IV). The thick terrestrial strata deposited in the units I and II provide not only a good regional caprock for the underlying (Z–T_2) marine oil/gas reservoirs, but are also a new prospective terrestrial target (T_3–K) for natural gas exploration (Liu et al., 2012; Jin et al., 2011; Zhao et al., 2010; Li W et al., 2009). Therefore, we argue that the thick terrestrial strata, weak deformation and minor magnitude of erosion contributed to better preservation conditions for hydrocarbons.

4.3 Differential Denudation Magnitude since Late Cretaceous and Natural Gas Accumulations

Denudation and removal of overburden often changes the structural style, pressure, temperature and salinity of the

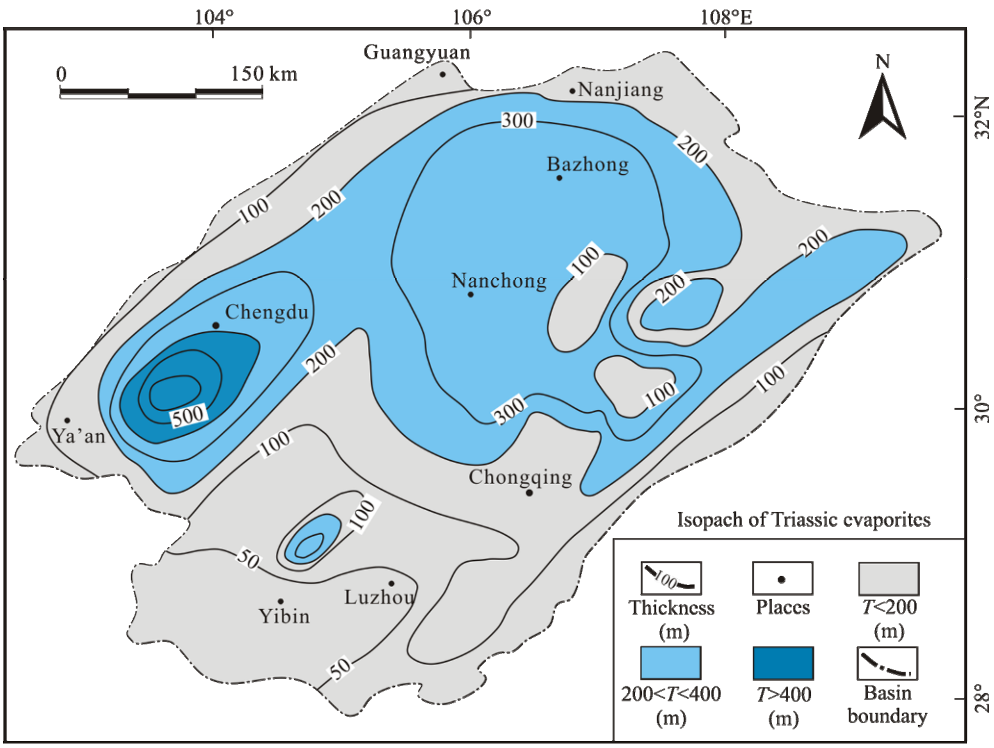

Figure 10. Isopach map of the Middle–Lower Triassic evaporites in the Sichuan Basin (modified after Jin et al., 2006). It suggests that there is more than 200 m thickness of Triassic evaporites across much of the Sichuan Basin, which could provide good conservation condition for hydrocarbon accumulation as a regional caprock.

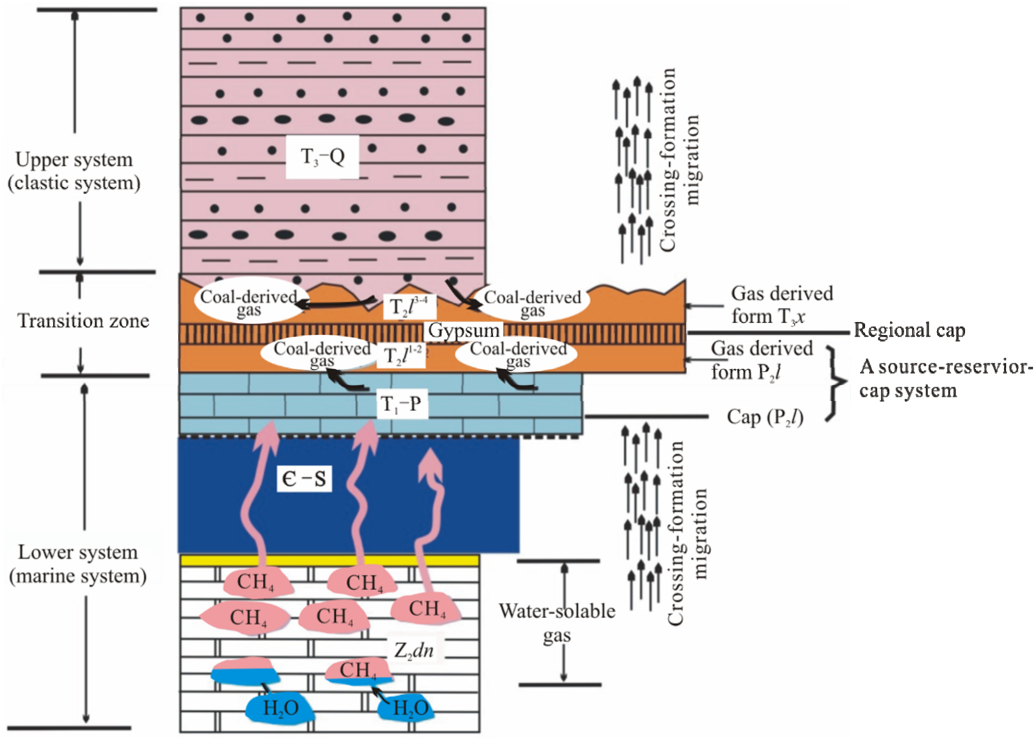

Figure 11. Model of cross-formation migration of the fluids during Jurassic–Cenozoic times in the Sichuan Basin, indicating of two systems of fluid flow separated by transition zone/regional cap of Middle Triassic Leikoupo Formation.

groundwater, etc., with profound effects on hydrocarbon systems (Liu et al., 2015b; Deng et al., 2014, 2011; Ohm et al., 2008; Doré et al., 2000).

In the Sichuan Basin hydrocarbon accumulation and fluid charge have been affected by the different denudation across the basin during Cenozoic time. It resulted in: (1) transformation of paleo gasfield to present-day gasfield. During the denudation process, the traps always have been exposed to some changes, e.g., erosion of caprock or reactivation of faults, resulting in the formation of a new trap and destruction of the previous one. Tian et al. (2008) and Ma et al. (2007) argued that the Puguang Gasfield shows an insignificant lateral shift of the peak of the trap, when the paleo gasfield was transformed to the present-day gasfield, with a gas preservation efficiency (ratio of proven in-place gas volume in present gasfield to that of paleo-gasfield) of oil-cracked gas being 75%–85%. Today there are very few petroleum accumulations at the basin boundary, where significant deformation and denudation destroyed the preservation condition for gas, particularly in the outer Sichuan Basin. Liu et al. (2010) calculated that there were significant prospective petroleum resources of 8.6×10^8 t in the Dingshan-Lintanchang paleo oilfield, located at the southern boundary of the Sichuan Basin. However, there is no gas accumulation today, due to the total destruction of preservation conditions. Hence, the adjustment or destruction of a paleo gas/oil field and its transformation to a present-day gasfield may vary due to the difference in the uplift, denudation, preservation, and structure of the trap. They are controlled by different basin boundary, resulting in significantly different preservation efficiencies for gas.

(2) Cross-formation migration of fluids and rapid accumulation of natural gas. Many fractures and faults were generated during deformation and denudation across the basin. They could accommodate the cross-formation migration of fluids, charge and accumulation of gas (Fig. 10). In the western Sichuan foreland basin (units I and II), fluids within the permeable layers of the 2rd and 4th members of the Upper Triassic Xujiahe Formation have flowed cross the impermeable layers of the 3rd and 5th members of the Upper Triassic Xujiahe Formation, to the permeable layers of the Jurassic sequences. Natural gas pools were formed because paleo-gas pools were fractured due to tectonic uplifting of the strata, resulting in cross-formation fluids flows. As a consequence natural gas was migrating and accumulated at high speeds and in large quantities through relatively narrow paths (faults and fractures). Such process of natural gas pools formation is called explosive accumulation (Liu S F et al., 2005), and is accompanied by a decrease in pressure from the underlying overpressure (pressure index 1.5–2.5) to upper normal pressure in the strata (pressure index 0.9–1.5) (Wang et al., 2004; He et al., 2001). Therefore, the thick terrestrial strata are new prospective terrestrial reservoirs (T_3–K) for petroleum accumulation, of which medium-large sized gasfields contribute 20.48% to total proven in-place reserves of the natural gas in the Sichuan Basin (Liu et al., 2012).

(3) It is likely that the previously dispersed natural gas, dissolved gas in formation water and coal-adsorbed gas (Bian et al., 2009; Liu et al., 2008d), re-migrate and charge the present-day traps, as the pressure and temperature changed due to the denudation in the Cenozoic, across the basin. Bian et al. (2009) and Zhao W Z et al. (2008) argued that the source rock desorbing and hydrocarbon discharge resulting from late denudation and unloading process, lead to the formation of medium-low to large oil/gasfields, e.g., the Guang'an Gasfield.

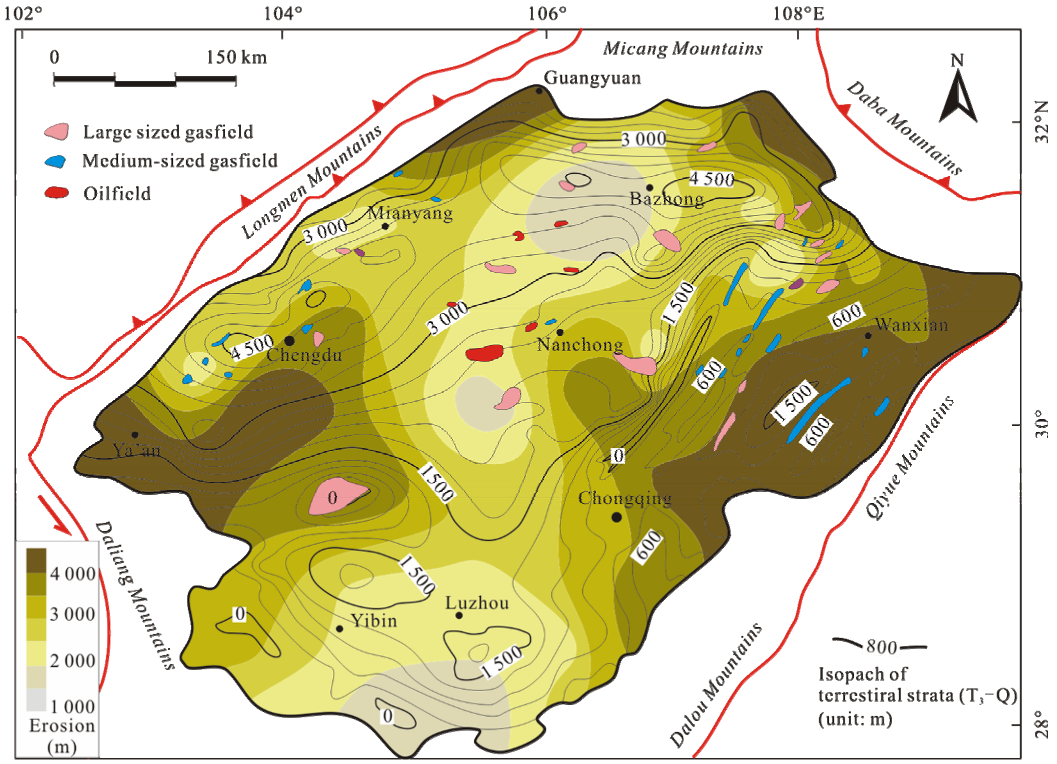

Figure 12. The composite features of sedimentary basin and orogenic belt system and the distribution of gas/oil fields in the Sichuan Basin. Magnitude of surface erosion is based on modeled thermal history of more than 100 apatite fission track data and vitrinite data (modified from Deng et al., 2013b). Isopach of terrestrial strata from Late Triassic Xujiahe Formation to Quaternary is based on 212 boreholes data and outcrop stratigraphic data (modified from Liu et al., 2012). It should be noted that there is a good correlation between the distribution of medium-to-large gasfields, large thickness of terrestrial deposits and small magnitude of denudation.

The multi-phase evolution of the Sichuan Basin significantly contributed to the diversity of petroleum systems, with abundant prospects for petroleum resources. The evolutionary phase of a marine carbonate platform in an extensional setting facilitated with deposits of abundant organic matter, in particular the intracratonic sags provide favorable conditions for the formation of assemblage of high-quality carbonate reservoir rock and mudstone source-rock (Tables 3, 5), and raise the efficiency and scale of the hydrocarbon accumulation. It has significant influence on the oil and gas occurrences along the margin of the sags in the interior of the Sichuan Basin (e.g., the Puguang Gasfiled, Anyue Gasfield). The second evolutionary phase of a foreland basin accommodated deep burial and high-maturity of all sets of source rocks across the Sichuan Basin (Tables 3, 5). At the same time, fold-and-thrust deformation around the basin has resulted in different types of basin-mountain systems, and widespread accumulation of the oil-cracked gas during this episode. During the Cenozoic times, widespread exhumation took place across the Sichuan Basin, resulting in cross-formation migration of fluids and rapid accumulation/adjustment of gas, in particular the western and central Sichuan Basin. It should be noted that some of paleo gasfields suffered with destroy of preservation condition during the Cenozoic times.

5 CONCLUSIONS

The Sichuan Basin, being a typical multi-stage basin, has experienced three evolutionary phases since Phanerozoic time as follows: (a) a marine carbonate platform in an extensional setting from the Ediacaran to Middle Triassic, (b) a foreland basin with fold-and-thrust deformation from Late Triassic to Late Cretaceous, and (c) subsequent exhumation and structural modification. Simultaneously, the Sichuan Basin also underwent three periods of tectonically driven changes. The first one is a transformation from an extensional to a contractional tectonic setting during the Late Triassic Period, which resulted into changed deposits from a marine carbonate in a passive continental margin to continental clastic deposition in the foreland basin. The second change occurred during the Late Cretaceous, resulting in migration of localized foredeeps and in a change from regional deposition to partial exhumation. The last change predominantly took place in the Eocene and is represented by the transformation of the sedimentary basin from deposition to basin-scale erosion.

The Sichuan Basin is characterized by a three-part subdivision in topography, basement and surface structure. The Sichuan Basin and its periphery can be further divided into two types of basin boundary, which can be sub-divided into five units: I. the North Sichuan unit controlled chiefly by the Qinling Orogen; II. West Sichuan unit controlled chiefly by the Tibetan Plateau; III. East Sichuan unit controlled chiefly by the intercontinental Xuefeng Orogen; IV. SW Sichuan unit controlled chiefly by the Xuefeng and Tibet orogens; and V. the central Sichuan unit controlled chiefly by the basement.

The Sichuan Basin, which is one of the major oil/gas basins in China, contains five sets of source rocks with cumulative thickness of up to 1 500–2 500 m. There are good preservation conditions for petroleum accumulation in the basin, due to the presence of Middle–Lower Triassic gypsum-salt rocks (>~200 m) and thick terrestrial sediments (>3 000 m) deposited in the western and northern Sichuan foreland basins (units I and II). However, different exhumation since the Late Cretaceous has exerted significant influence on cross-formation migration of fluids and rapid accumulation of gas. The multiphase evolution of the Sichuan Basin, different tectonic systems and petroleum geologic conditions in the basin significantly contributed to the diversity of petroleum systems, with abundant prospects for petroleum resources.

ACKNOWLEDGMENTS

This work was supported by the National Basic Research Program of China (No. 2012CB214805), the National Natural Science Foundation of China (Nos. 41230313, 41402119, 2017JQ0025, 41472017, 41572111). We are thankful to Frank Thomas for review of the English in the manuscript. The final publication is available at Springer via https://doi.org/10.1007/s12583-017-0904-8.

REFERENCES CITED

Allen, P. A., Allen, J. R., 2013. Basin Analysis: Principles and Application to Petroleum Play Assessment. Wiley-Blackwell, West Sussex. 633

BGMRSP (Bureau of Geology and Mineral Resources of Sichuan Province), 1991. Regional Geology of Sichuan Province. Geological Publishing House, Beijing. 701 (in Chinese)

Bian, C. S., Wang, H. J., Wang, Z. C., et al., 2009. Controlling Factors for Massive Accumulation of Natural Gas in the Xujiahe Formation in Central Sichuan Basin. *Oil and Gas Geology*, 30(5): 548–556 (in Chinese with English Abstract)

Blackmer, G. C., Omar, G. I., Gold, D. P., 1994. Post-Alleghanian Unroofing History of the Appalachian Basin, Pennsylvania, from Apatite Fission Track Analysis and Thermal Models. *Tectonics*, 13(5): 1259–1276. https://doi.org/10.1029/94tc01507

Burchfiel, B. C., Chen, Z. L., Yupinc, L., et al., 1995. Tectonics of the Longmen Shan and Adjacent Regions, Central China. *International Geology Review*, 37(8): 661–735. https://doi.org/10.1080/00206819509465424

Burchfiel, B. C., Royden, L. H., van der Hilst, R. D., et al., 2008. A Geological and Geophysical Context for the Wenchuan Earthquake of 12 May 2008, Sichuan, People's Republic of China. *GSA Today*, 18(7): 4. https://doi.org/10.1130/gsatg18a.1

Chen, G. Q., Gong, C. M., Wang, L., et al., 2007. Gas Accumulation Condition in the Xujiahe Group of Guang'an Area. *Natural Gas Industry*, 27(6): 1–5 (in Chinese with English Abstract)

Chen, H., Hu, J. M., Qu, H. J., et al., 2011. Early Mesozoic Structural Deformation in the Chuandian NS Tectonic Belt, China. *Science China Earth Sciences*, 54(11): 1651–1664. https://doi.org/10.1007/s11430-011-4261-7

Chen, S. F., Wilson, C. J. L., 1996. Emplacement of the Longmen Shan Thrust—Nappe Belt along the Eastern Margin of the Tibetan Plateau. *Journal of Structural Geology*, 18(4): 413–430. https://doi.org/10.1016/0191-8141(95)00096-v

Cheng, S. Y., Zhang, G. W., Li, L., 2003. Lithospheric Electrical Structure of the Qinling Orogen and Its Geodynamic Implication. *Chinese Journal of Geophysics*, 46(3): 556–567. https://doi.org/10.1002/cjg2.3373

Clark, M. K., Schoenbohm, L. M., Royden, L. H., et al., 2004. Surface Uplift, Tectonics, and Erosion of Eastern Tibet from Large-Scale Drainage Patterns. *Tectonics*, 23(1): 1–20. https://doi.org/10.1029/2002tc001402

Deng, B., Li, Z. W., Liu, S. G., et al., 2016. Structural Geometry and Kinematic Processes at the Intracontinental Daloushan Mountain Chain: Implications for Tectonic Transfer in the Yangtze Block Interior. *Comptes Rendus Geoscience*, 348(2): 159–168. https://doi.org/10.1016/j.crte.2015.06.009

Deng, B., Liu, S. G., Enkelmann, E., et al., 2014. Late Miocene Accelerated Exhumation of the Daliang Mountains, Southeastern Margin of the Tibetan Plateau. *International Journal of Earth Sciences*, 104(4): 1061–1081. https://doi.org/10.1007/s00531-014-1129-z

Deng, B., Liu, S. G., Jansa, L., et al., 2012a. Sedimentary Record of Late Triassic Transpressional Tectonics of the Longmenshan Thrust Belt, SW China. *Journal of Asian Earth Sciences*, 48(6): 43–55. https://doi.org/10.1016/j.jseaes.2011.12.019

Deng, B., Liu, S. G., Li, Z. W., et al., 2012b. Late Cretaceous Tectonic Change of the Eastern Margin of the Tibetan Plateau—Results from Multisystem Thermochronology. *Journal of the Geological Society of India*, 80(2): 241–254. https://doi.org/10.1007/s12594-012-0134-8

Deng, B., Liu, S. G., Li, J. C., et al., 2011. The Coupling of Fluid Flow and Uplift since Late Cretaceous in Zoige Area, Western Sichuan. *Science China Earth Sciences*, 54(7): 1043–1052. https://doi.org/10.1007/s11430-011-4185-2

Deng, B., Liu, S. G., Liu, S., et al., 2009. Restoration of Exhumation Thickness and Its Significance in Sichuan Basin, China. *Journal of Chengdu University of Technology* (*Science & Technology Edition*), 36(6): 675–687 (in Chinese with English Abstract)

Deng, B., Liu, S. G., Jansa, L., et al., 2013a. Fractal Analysis of Veins in Permian Carbonate Rocks in the Lingtanchang Anticline, Western China. *Geofluids*, 14(2): 160–173. https://doi.org/10.1111/gfl.12059

Deng, B., Liu, S. G., Li, Z. W., et al., 2013b. Differential Exhumation at Eastern Margin of the Tibetan Plateau, from Apatite Fission-Track Thermochronology. *Tectonophysics*, 591: 98–115. https://doi.org/10.1016/j.tecto.2012.11.012

Deng, K. L., 2007. Indosinian Progressive Deformation and Its Chronogenesis in Longmenshan Structural Belt. *Oil & Gas Geology*, 28(4): 485–491 (in Chinese with English Abstract)

Dong, L. F., Liu, Q. Y., Sun, D. S., et al., 2015. Generation, Preservation and Accumulation of Natural Gas in Jiannan Gasfield. *Natural Gas Geoscience*, 26(4): 657–666 (in Chinese with English Abstract)

Dong, Y. P., Zha, X. F., Fu, M. Q., et al., 2008. Characteristics of the Dabashan Fold-Thrust Nappe Structure at the Southern Margin of the Qingling, China. *Geological Bulletin of China*, 23(4): 269–280 (in Chinese with English Abstract)

Dong, Y. P., Zhang, G. W., Neubauer, F., et al., 2011. Tectonic Evolution of the Qinling Orogen, China: Review and Synthesis. *Journal of Asian Earth Sciences*, 41(3): 213–237. https://doi.org/10.1016/j.jseaes.2011.03.002

Doré, A. G., Scotchman, I. C., Corcoran, D., 2000. Cenozoic Exhumation and Prediction of the Hydrocarbon System on the NW European Margin. *Journal of Geochemical Exploration*, 69/70: 615–618. https://doi.org/10.1016/s0375-6742(00)00137-0

Enkelmann, E., Ratschbacher, L., Jonckheere, R., et al., 2006. Cenozoic Exhumation and Deformation of Northeastern Tibet and the Qinling: Is Tibetan Lower Crustal Flow Diverging around the Sichuan Basin?. *Geological Society of America Bulletin*, 118(5/6): 651–671. https://doi.org/10.1130/b25805.1

Guo, T. L., 2013. Evaluation of Highly Thermally Mature Shale-Gas Reservoirs in Complex Structural Parts of the Sichuan Basin. *Journal of Earth Science*, 24(6): 863–873. https://doi.org/10.1007/s12583-013-0384-4

Guo, Z. W., Deng, K. L., Han, Y. F., 1996. Formation and Evolution of the Sichuan Basin. Geological Publishing House, Beijing. 201 (in Chinese)

He, Z. G., Wang, X., Li, C. J., et al., 2001.The Relationship between Overpressure in Terrestrial Clastic Rock and Petroleum Accumulation in Western Sichuan Basin. *Natural Gas Exploration and Development*, 24(4): 6–15 (in Chinese with English Abstract)

Huang, J. Z., 1998. A Discussion on the Replaced Tracts for Natural Gas Exploration in Sichuan Basin. *Natural Gas Industry*, 18(1): 13–17 (in Chinese with English Abstract)

Huang, J. Z., Chen, S. J., Song, J. R., et al., 1997. Hydrocarbon Source Systems and Formation of Gas Fields in Sichuan Basin. *Science in China Series D: Earth Sciences*, 40(1): 32–42. https://doi.org/10.1007/bf02878579

Hubbard, J., Shaw, J. H., 2009. Uplift of the Longmen Shan and Tibetan Plateau, and the 2008 Wenchuan (M_s=7.9) Earthquake. *Nature*, 458(7235): 194–197. https://doi.org/10.1038/nature07837

Jia, D., Wei, G. Q., Chen, Z. X., et al., 2006. Longmen Shan Fold-Thrust Belt and Its Relation to the Western Sichuan Basin in Central China: New Insights from Hydrocarbon Exploration. *AAPG Bulletin*, 90(9): 1425–1447. https://doi.org/10.1306/03230605076

Jiang, X. D., Jin, Y., 2005. Mapping the Deep Lithospheric Structure beneath the Eastern Margin of the Tibetan Plateau from Gravity Anomalies. *Journal of Geophysical Research*, 110(B7): 1–14. https://doi.org/10.1029/2004jb003394

Jin, C., Li, S. Z., Wang, Y. J., et al., 2009. Diachronous and Progressive Deformation during the Indosinian-Yanshanian Movements of Xuefeng Mountain Intracontinental Composite Tectonic System. *Oil & Gas Geology*, 30(5): 598–608 (in Chinese with English Abstract)

Jin, W. Z., Tang, L. J., Yang, K. M., et al., 2009. Transfer Zones within the Longmen Mountains Thrust Belt, SW China. *Geosciences Journal*, 13(1): 1–14. https://doi.org/10.1007/s12303-009-0001-9

Jin, W. Z., Wan, G. M., Wang, J. P., et al., 2011. Distribution Characteristic and Genetic Mechanism of Hydrocarbon Traps of the Terrestrial Clastic Rock in Sichuan Basin. *Acta Geologica Sinica*, 85(10): 1673–1680 (in Chinese with English Abstract)

Jin, Z. J., Long, S. X., Zhou, Y., et al., 2006. A Study on the Distribution of Saline-Deposit in Southern China. *Oil & Gas Geology*, 27(5): 571–583 (in Chinese with English Abstract)

Korsch, R. J., Mai, H. Z., Sun, Z. C., et al., 1991. The Sichuan Basin, Southwest China: A Late Proterozoic (Sinian) Petroleum Province. *Precambrian Research*, 54(1): 45–63. https://doi.org/10.1016/0301-9268(91)90068-l

Li, J. Z., Dong, D. Z., Chen, G. S., et al., 2009. Prospects and Strategic Position of Shale Gas Resources in China. *Natural Gas Industry*, 29(5): 11–16 (in Chinese with English Abstract)

Li, W., Yang, J. L., Jiang, J. W., et al., 2009. Origin of Upper Triassic Formation Water in Middle Sichuan Basin and Its Natural Gas Significance. *Petroleum Exploration and Development*, 36(4): 428–435. https://doi.org/10.1016/s1876-3804(09)60138-5

Li, Y., Allen, P. A., Densmore, A. L., et al., 2003. Evolution of the Longmen Shan Foreland Basin (Western Sichuan, China) during the Late Triassic Indosinian Orogeny. *Basin Research*, 15(1): 117–138. https://doi.org/10.1046/j.1365-2117.2003.00197.x

Li, Z. W., Liu, S. G., Chen, H. D., et al., 2012. Spatial Variation in Meso-Cenozoic Exhumation History of the Longmen Shan Thrust Belt (Eastern Tibetan Plateau) and the Adjacent Western Sichuan Basin: Constraints from Fission Track Thermochronology. *Journal of Asian Earth Sciences*, 47(1): 185–203. https://doi.org/10.1016/j.jseaes.2011.10.016

Li, Z. W., Liu, S. G., Luo, Y. H., et al., 2007. Structural Style and Deformation Mechanism of the Southern Dabashan Foreland Fold-and-Thrust Belt, Central China. *Frontiers of Earth Science in China*, 1(2): 181–193. https://doi.org/10.1007/s11707-007-0023-4

Liu, S. F., Steel, R., Zhang, G. W., 2005. Mesozoic Sedimentary Basin Development and Tectonic Implication, Northern Yangtze Block, Eastern China: Record of Continent-Continent Collision. *Journal of Asian Earth Sciences*, 25(1): 9–27. https://doi.org/10.1016/j.jseaes.2004.01.010

Liu, S. G., Deng, B., Li, Z. W., et al., 2012. Architecture of Basin-Mountain Systems and Their Influences on Gas Distribution: A Case Study from the Sichuan Basin, South China. *Journal of Asian Earth Sciences*, 47(1): 204–215. https://doi.org/10.1016/j.jseaes.2011.10.012

Liu, S. G., Li, G. R., Li, J. C., et al., 2005. Fluid cross Formation Flow and Gas Explosion Accumulation in Western Sichuan Foreland Basin, China. *Acta Geologica Sinica*, 79(5): 690–699 (in Chinese with English Abstract)

Liu, S. G., Li, Z. W., Liu, S., et al., 2006. Formation and Evolution of Dabashan Foreland Basin and Fold-and-Thrust Belt, Sichuan, China. Geological Publishing House, Beijing. 223 (in Chinese)

Liu, S. G., Luo, Z. L., Dai, S. L., et al., 1996. The Uplift of the Longmenshan Thrust Belt and Subsidence of the West Sichuan Foreland Basin. *Acta Geologica Sinica*, 9(1): 16–26 (in Chinese with English Abstract)

Liu, S. G., Sun, W., Luo, Z. L., et al., 2013a. Xinghai Taphrogenesis and Petroleum Exploration from Upper Sinian to Cambrian Strata in Sichuan Basin, China. *Journal of Chengdu University of Technology* (*Sciences & Technology Edition*), 40(5): 511–520 (in Chinese with English Abstract)

Liu, S. G., Deng, B., Li, Z. W., et al., 2013b. Geological Evolution of the Longmenshan Intracontinental Composite Orogen and the Eastern Margin of the Tibetan Plateau. *Journal of Earth Science*, 24(6): 874–890. https://doi.org/10.1007/s12583-013-0391-5

Liu, S. G., Sun, W., Zhao, Y. H., et al., 2015a. Differential Accumulation and Distribution of Natural Gas and Its Main Controlling Factors in the Sinian Dengying Fm, Sichuan Basin. *Natural Gas Industry B*, 2(1): 24–36. https://doi.org/10.1016/j.ngib.2015.02.003

Liu, S. G., Sun, W., Song, J. M., et al., 2015b. Tectonics-Controlled Distribution of Marine Petroleum Accumulations in the Sichuan Basin, China. *Earth Science Frontiers*, 22(3): 146–160 (in Chinese with English Abstract)

Liu, S. G., Wang, H., Sun, W., et al., 2008a. Analysis of Special Feature of Petroleum Geological Conditions of Marine Facies in Sichuan Basin. *Oil & Gas Geology*, 29(6): 781–793 (in Chinese with English Abstract)

Liu, S. G., Sun, W., Li, Z. W., et al., 2008b. Tectonic Uplifting and Gas Pool Formation since Late Cretaceous Epoch, Sichuan Basin. *Natural Gas Geoscience*, 19(3): 293–300 (in Chinese with English Abstract)

Liu, S. G., Ma, Y. S., Sun, W., et al., 2008c. Studying on the Difference of Sinian Natural Gas Pools between Weiyuan Gas Field and Ziyang Gas-Brone Area, Sichuan Basin. *Acta Geologica Sinica*, 82(3): 328–337 (in Chinese with English Abstract)

Liu, S. G., Wang, H., Sun, W., et al., 2008d. Energy Field Adjustment and Hydrocarbon Phase Evolution in Sinian–Lower Paleozoic, Sichuan Basin. *Journal of China University of Geosciences*, 19(6): 700–706

Liu, S. G., Li, Z. W., Cao, J. X., et al., 2009a. 4-D Trxtural and Structural Characteristics of Longmen Intracontinental Composite Orogenic Belt, Southwest China. *Chinese Journal of Geology*, 44(4): 1151–1180 (in Chinese with English Abstract)

Liu, S. G., Yang, R. J., Wu, X. C., et al., 2009b. The Late Triassic Transition from Marine Carbonate Rock to Clastics in the Western Sichuan Basin. *Oil & Gas Geology*, 30(5): 556–565 (in Chinese with English

Abstract)

Liu, S. G., Zeng, X. L., Huang, W. M., et al., 2009c. Basic Characteristics of Shale and Continuous-Discontinuous Transition Gas Reservoirs in Sichuan Basin, China. *Journal of Chengdu University of Technology* (*Science & Technology Edition*), 36(6): 578–592 (in Chinese with English Abstract)

Liu, S. G., Zhang, Z. J., Huang, W. M., et al., 2010. Formation and Destruction Processes of Upper Sinian Oil-Gas Pools in the Dingshan-Lintanchang Structural Belt, Southeast Sichuan Basin, China. *Petroleum Science*, 7(3): 289–301. https://doi.org/10.1007/s12182-010-0071-3

Liu, Z. C., Hu, S. Y., Li, F. B., et al., 2017. Progress and Prospects of Shale Gas Exploration and Development in Sichuan, China. *Journal of Clean Energy Technologies*, 5(3): 258–262. https://doi.org/10.18178/jocet.2017.5.3.379

Luo, Z. L., 1998. New Recognition of Basement in Sichuan Basin. *Journal of Chengdu University of Technology* (*Science & Technology Edition*), 25(2): 191–200 (in Chinese with English Abstract)

Luo, Z. L., Zhao, X. K., Liu, S. G., et al., 2001. Establishment and Development of "Chinese Taphrogenyoutlool". *Petroleum Geology & Experiment*, 23(2): 232–231 (in Chinese with English Abstract)

Luo, Z. L., Zhao, X. K., Liu, S. G., et al., 1994. Uplift of Longmen Mountain Orogenic Belt and the Formation and Evolution of Sichuan Basin. Chengdu University of Technology Press, Chengdu. 474 (in Chinese)

Ma, Y. S., Cai, X. Y., Zhao, P. R., et al., 2010. Distribution and Further Exploration of the Large-Medium Sized Gas Fields in Sichuan Basin. *Acta Petrolei Sinica*, 31(3): 347–354 (in Chinese with English Abstract)

Ma, Y. S., Guo, X. S., Guo, T. L., et al., 2007. The Puguang Gas Field: New Giant Discovery in the Mature Sichuan Basin, Southwest China. *AAPG Bulletin*, 91(5): 627–643. https://doi.org/10.1306/11030606062

OGSCGS (Oil and Gas Survey of China Geological Survey), 2013. Research Report on the Shale Gas Exploration and Development in China, Oil and Gas Survey of China Geological Survey, Beijing (in Chinese)

Ohm, S. E., Karlsen, D. A., Austin, T. J. F., 2008. Geochemically Driven Exploration Models in Uplifted Areas: Examples from the Norwegian Barents Sea. *AAPG Bulletin*, 92(9): 1191–1223. https://doi.org/10.1306/06180808028

Plesch, A., Shaw, J. H., Kronman, D., 2007. Mechanics of Low-Relief Detachment Folding in the Bajiaochang Field, Sichuan Basin, China. *AAPG Bulletin*, 91(11): 1559–1575. https://doi.org/10.1306/06200706072

Reiners, P. W., Zhou, Z. Y., Ehlers, T. A., et al., 2003. Post-Orogenic Evolution of the Dabie Shan, Eastern China, from (U-Th)/He and Fission-Track Thermochronology. *American Journal of Science*, 303(6): 489–518. https://doi.org/10.2475/ajs.303.6.489

Richardson, N. J., Densmore, A. L., Seward, D., et al., 2008. Extraordinary Denudation in the Sichuan Basin: Insights from Low-Temperature Thermochronology Adjacent to the Eastern Margin of the Tibetan Plateau. *Journal of Geophysical Research*, 113(B4): B04409. https://doi.org/10.1029/2006jb004739

Robert, A., Zhu, J., Vergne, J., et al., 2010. Crustal Structures in the Area of the 2008 Sichuan Earthquake from Seismologic and Gravimetric Data. *Tectonophysics*, 491(1–4): 205–210. https://doi.org/10.1016/j.tecto.2009.11.010

Shen, C. B., Mei, L. F., Xu, S. H., 2009. Fission Track Dating of Mesozoic Sandstones and Its Tectonic Significance in the Eastern Sichuan Basin, China. *Radiation Measurements*, 44(9/10): 945–949. https://doi.org/10.1016/j.radmeas.2009.10.001

Shi, W., Zhang, Y. Q., Dong, S. W., et al., 2012. Intra-Continental Dabashan Orocline, Southwestern Qinling, Central China. *Journal of Asian Earth Sciences*, 46(6): 20–38. https://doi.org/10.1016/j.jseaes.2011.10.005

Sun, W., Liu, S. G., Ma, Y. S., et al., 2007. Determination and Quantitative Simulation of Gas Pool Formation Process of Sinian Cracked Gas in Weiyuan-Ziyang Area, Sichuan Basin. *Acta Geologica Sinica*, 81(8): 1153–1159 (in Chinese with English Abstract)

Sun, W., Liu, S. G., Xu, G. S., et al., 2011. Formation Model of Marine Carbonate Natural Gas Pools in the Deep Part of the Sichuan Basin, China. *Acta Petrologica Sinica*, 27(8): 2349–2361 (in Chinese with English Abstract)

Tian, H., Xiao, X. M., Wilkins, R. W. T., et al., 2008. New Insights into the Volume and Pressure Changes during the Thermal Cracking of Oil to Gas in Reservoirs: Implications for the in-situ Accumulation of Gas Cracked from Oils. *AAPG Bulletin*, 92(2): 181–200. https://doi.org/10.1306/09210706140

Wang, E. Q., Burchfiel, B. C., 2000. Late Cenozoic to Holocene Deformation in Southwestern Sichuan and Adjacent Yunnan, China, and Its Role in Formation of the Southeastern Part of the Tibetan Plateau. *Geological Society of America Bulletin*, 112(3): 413–423. https://doi.org/10.1130/0016-7606(2000)112<413:lcthdi>2.0.co;2

Wang, E. Q., Yin, J. Y., 2009. Cenozoic Multi-Stage Deformation Occurred in Southwest Sichuan: Cause for the Dismemberment of the Proto-Sichuan Basin. *Journal of Northwest University* (*Natural Science Edition*), 39(3): 359–367 (in Chinese with English Abstract)

Wang, G. Z., Liu, S. G., 2009. Paleo-Fluid Geochemical Evaluation of Hydrocarbon Preservation in Marine Carbonate Rock Areas: Taking Lower Association in Central Sichuan Basin as an Example. *Journal of Chengdu University of Technology* (*Science & Technology Edition*), 36(6): 631–644 (in Chinese with English Abstract)

Wang, J. Q., 1996. Relationship between Tectonic Evolution and Hydrocarbon in the Foreland of the Longmen Mountains. *Journal of Southeast Asian Earth Sciences*, 13(3–5): 327–336. https://doi.org/10.1016/0743-9547(96)00039-6

Wang, M. J., 1994. Gravity and Magnetic Interpretation of Heishui-Quanzhou Geoscience Transect. *Acta Geophysica Sinica*, 37(3): 321–329 (in Chinese with English Abstract)

Wang, S. Q., Chen, G. S., Huang, X. P., 2005. Petroleum Resource Potential and Major Exploration Areas in Sichuan Basin. *Acta Petrolei Sinica*, 26(b03): 97–101 (in Chinese with English Abstract)

Wang, Y. G., Wen, Y. C., Zhang, F., et al., 1998. Distribution Law of the Organic Reefs in Changxing Formation of Upper Permian in East Sichuan. *Natural Gas Industry*, 18(6): 10–15 (in Chinese with English Abstract)

Wang, Z. C., Zhao, W. Z., Zhang, L., et al., 2002. Tectonic Sequence and Natural Gas Exploration in Sichuan Basin. Geological Publishing House, Beijing. 290 (in Chinese)

Wang, Z. L., Sun, M. L., Zhang, L. K., et al., 2004. Evolution of Abnormal Pressure and Model of Gas Accumulation in Xujiahe Formation, Western Sichuan Basin. *Earth Science—Journal of China University of Geosciences*, 29(4): 433–439 (in Chinese with English Abstract)

Wang, Z. S., Zhao, G. Z., Tang, J., et al., 2010. The Electrical Structure of the Crust along Mianning-Yibin Profile in the Eastern Edge of Tibetan Plateau and Its Tectonic Implications. *Chinese J. Geophys.*, 53(3): 585–594 (in Chinese with English Abstract)

Wang, Z. X., Zhang, J., Li, T., et al., 2010. Structural Analysis of the Multi-Layer Detachment Folding in Eastern Sichuan Province. *Acta Geologica Sinica—English Edition*, 84(3): 497–514. https://doi.org/10.1111/j.1755-6724.2010.00269.x

Wilson, C. J. L., Fowler, A. P., 2011. Denudational Response to Surface Uplift in East Tibet: Evidence from Apatite Fission-Track Thermochronology. *Geological Society of America Bulletin*, 123(9/10): 1966–1987. https://doi.org/10.1130/b30331.1

Wu, S. X., Ma, Y. S., Jin, Z. J., et al., 2006. Tectonic Evolution and Oil and Gas Accumulation in the East Micangshan Foreland Basin, Sichuan. *Petroleum Exploration and Development*, 2(1): 14–17 (in Chinese with English Abstract)

Wu, X. C., 1989. Carnian (Upper Triassic) Sponge Mounds of the Northwestern Sichuan Basin, China: Stratigraphy, Facies and Paleoecology. *Facies*, 21(1): 171–187. https://doi.org/10.1007/bf02536835

Xia, Z. S., 1982. Continental Mesozoic Stratigraphy and Paleontology in Sichuan Basin of China, Part 1, Stratigraphy. People's Publishing House of Sichuan, Chengdu. 743 (in Chinese)

Xu, Y. C., Shen, P., 1996. A Study of Natural Gas Origins in China. *AAPG Bulletin*, 80(10): 1604–1614. https://doi.org/10.1306/64eda0c8-1724-11d7-8645000102c1865d

Yan, C. Z., Huang, Y. Z., Ge, C. M., et al., 2009. Shale Gas: Enormous Potential of Unconventional Natural Gas Resources. *Natural Gas Industry*, 29(5): 1–6 (in Chinese with English Abstract)

Yan, D. P., Zhang, B., Zhou, M. F., et al., 2009. Constraints on the Depth, Geometry and Kinematics of Blind Detachment Faults Provided by Fault-Propagation Folds: An Example from the Mesozoic Fold Belt of South China. *Journal of Structural Geology*, 31(2): 150–162. https://doi.org/10.1016/j.jsg.2008.11.005

Yan, D. P., Zhou, M. F., Song, H. L., et al., 2003. Origin and Tectonic Significance of a Mesozoic Multi-Layer Over-Thrust System within the Yangtze Block (South China). *Tectonophysics*, 361(3/4): 239–254. https://doi.org/10.1016/s0040-1951(02)00646-7

Yang, K. M., Ye, J., Lu, Z. X., 2005. Chronological Characteristics of Upper Triassic Reservoirs in Western Sichuan Depression. *Oil & Gas Geology*, 26(2): 208–213 (in Chinese with English Abstract)

Yang, R. J., Liu, S. G., Wu, X. C., 2010. Distribution and Formation Mechanism of Lime Mudstone in Upper Triassic in Northwestern Sichuan, China. *Carbonates and Evaporites*, 25(4): 275–281. https://doi.org/10.1007/s13146-010-0035-0

Yue, G. Y., Du, S. Q., Huang, J. J., et al., 1996. Principle of Structural Compounding-Combine: Analysis of Structural Association-Superposition in Sichuan Basin and Guizhou Plateau, China. Chengdu University of Technology Press, Chengdu. 285 (in Chinese)

Zhang, J., Zhang, Q., 2002. The Review and Prospects of Oil and Gas Exploration in Sichuan Basin. *Natural Gas Industry*, 22(Suppl.1): 3–7 (in Chinese with English Abstract)

Zhang, S. C., Zhu, G. Y., 2006. Gas Accumulation Characteristics and Exploration Potential of Marine Sediments in Sichuan Basin. *Acta Petrolei Sinica*, 27(5): 1–8 (in Chinese with English Abstract)

Zhang, Y. Q., Dong, S. W., Li, J. H., et al., 2011. Mesozoic Multi-Directional Compressional Tectonics and Formation-Reformation of Sichuan Basin. *Geology in China*, 38(2): 234–250 (in Chinese with English Abstract)

Zhao, W. Z., Wang, H. J., Yuan, X. J., et al., 2010. Petroleum Systems of Chinese Nonmarine Basins. *Basin Research*, 22(1): 4–16. https://doi.org/10.1111/j.1365-2117.2009.00451.x

Zhao, W. Z., Wang, Z. C., Wang, H. J., et al., 2008. Principal Characteristics and Forming Conditions for Medium-Low Abundance Large Scale Oil/Gas Fields in China. *Petroleum Exploration and Development*, 35(6): 641–650. https://doi.org/10.1016/s1876-3804(09)60097-5

Zhao, X. F., Lu, Z. G., Zhang, W. L., et al., 2008. Paralic Tidal Deposits in the Upper Triassic Xujiahe Formation in Anyue Area, the Sichuan Basin. *Natural Gas Industry*, 28(4): 128–134 (in Chinese with English Abstract)

Zheng, J. P., Griffin, W. L., O'Reilly, S. Y., et al., 2006. Widespread Archean Basement beneath the Yangtze Craton. *Geology*, 34(6): 417. https://doi.org/10.1130/g22282.1

Zhong, C., Huang, J., 1997. Drilling and Gas Recovery Technology in Ancient China. Zigong Salt Industry Museum, Zigong. 44 (in Chinese with English Abstract)

Zhou, J. Y., Wu, C. L., Han, Z. J., 1997. Crustal Thermal Structure Model and Thermal Evolution along the Sichuan Basin Segment of the Heishui-Quanzhou Geotraverse. *Acta Geologica Sichuan*, 17(3): 161–167 (in Chinese with English Abstract)

Zou, C. N., Du, J. H., Xu, C. C., et al., 2014. Formation, Distribution, Resource Potential, and Discovery of Sinian–Cambrian Giant Gas Field, Sichuan Basin, SW China. *Petroleum Exploration and Development*, 41(3): 306–325. https://doi.org/10.1016/s1876-3804(14)60036-7